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THE FEASIBILITY OF WIRELESS POWER TRANSMISSION
FOR AN ORBITING ASTRONOMICAL STATION (REVISED)

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May 27, 1969

NASA

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16. Abstract An examination is made of the feasibility of using microwave or laser energy for wireless transfer of power from a manned, Earth-orbiting central station to unmanned astronomical substations. This is a recent conception, and details of a power-transfer system have not been established. Therefore, the possibility of wireless power transfer is judged on the basis of the state of research and development in power generation, transmission, and conversion.			
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THE FEASIBILITY OF WIRELESS POWER TRANSMISSION FOR AN ORBITING ASTRONOMICAL STATION (REVISED)

SUMMARY

An examination is made of the feasibility of using microwave or laser energy for wireless transfer of power from a manned, Earth-orbiting central station to unmanned astronomical substations. This is a recent conception, and details of a power-transfer system have not been established. Therefore, the possibility of wireless power transfer is judged on the basis of the state of research and development in power generation, transmission, and conversion.

Existing microwave power generation is more than adequate for the estimated 2 kW requirement of a satellite substation. Generators such as superpower Amplitrons have a laboratory output exceeding 400 kW of CW power at a wavelength of 10 cm. In an unoptimized power system (including generation, transmission, and conversion) with an overall efficiency of 18 percent, an Amplitron could supply power for several substations.

Microwave power transmission would require better efficiency than is acceptable for present radar and communication systems. One idea for improving efficiency is to form a convergent beam in an ellipsoidal transmission "envelope."

Calculations involving the relationship between antenna size and operating wavelength show that antenna size can be reduced as wavelength is reduced. However, generator efficiency also diminishes with shorter wavelength. The implication is that improvement of generator efficiency for operation at shorter wavelengths (less than 3 cm) would permit a significant reduction in antenna size.

Direct conversion of microwave to dc power is a more recent development than power generation. Semiconductor diodes and close-spaced thermionic diode rectifiers are considered the most promising components for aerospace applications.

A microwave power transfer system has already been used experimentally to operate a helicopter device; and a beam-riding system has been developed so that the same microwave beam may be used to control the position of a distant helicopter.

The present availability and performance of microwave components and the progress being made in research and development point to the feasibility of a practical wireless power-transfer system for aerospace use within a few years.

Laser high-power development, being newer, is behind microwave technology. The highest power attained in the laboratory has been 9 kW, with a CO₂-N₂-He medium. Despite the short history of its development, however, power generation is progressing rapidly.

Laser power transmission and conversion still are in the research stage. One of the goals of research in power transmission is to obtain a long-lived refractor that will withstand high-power radiation. Lenses of doped germanium (Ge-Sb-Se) and of ultrapure germanium are being tested for this use.

Laser energy has been converted to electric power by means of photo-voltaic detectors. These are semiconductor diodes with p-n junctions of Cd-Hg-Te alloys, and can be made for efficient operation at the CO₂-laser wavelength.

Calculations similar to those made for microwave antenna size show that transmission and receiving apertures would be much smaller for the laser beam. This offers a special advantage over a microwave system, which must compromise between transfer efficiency and antenna size.

INTRODUCTION

The objectives of future astronomical payloads (beyond the follow-on Apollo Telescope Mount) have been the subject of much discussion and planning [1]. To help fulfill these objectives, a concept of an Earth-orbiting astronomical station has been proposed. The concept envisions a large, manned central station and small, unmanned satellite substations several kilometers from the central station. Each substation would be designed for a specific program.

The central station would support an astronaut crew and provide electric power, a workshop and laboratory, data transmission systems, shielded film storage, docking facilities, etc. For the concept of untethered substations, which this report is concerned with, the electrical power obtained from a nuclear reactor generator would be converted to electromagnetic energy in the form of microwaves or monochromatic light. This energy would be transmitted to the substations, thus serving as a source of electrical power and, possibly, for guidance and control. All the substation power requirements would be met through suitable conversion of the electromagnetic energy received from the central station.

With this conception, changes in the scientific programs would require only the addition of a new substation having its telescope and recording equipment designed for the particular program. The cost of each new substation in time and money would be relatively small since such features as control and pointing systems, power source, and launch systems would be standard for all substations.

The concept of electric-power transmission through microwaves is not new, of course, being first attempted in 1899 by Tesla [2, 3]. Since that early, unsuccessful experiment, industry has successfully developed microwave equipment which generates hundreds of kilowatts for radar, heating, and other applications [4, 5, 6, 31]. In a recent example of wireless power transmission, a helicopter device operated aloft, deriving its electric power from microwave energy beamed from a ground-based generator [2, 3, 29, 30, 32].

Laser generation and transmission of energy for conversion to electric power has not reached the same stage of development as in microwaves. The potentialities of lasers, however, warrant serious consideration of their use for power transmission. Consequently, although this report deals mainly with microwaves as a feasible power system, the possibilities of laser application are also considered.

An artist's conception of the orbiting astronomical station is shown in Figures 1 and 2, and the basic plan of electromagnetic energy transfer is illustrated diagrammatically in Figure 3. The research and developmental status of these basic elements in microwave and laser systems is examined in this report as the basis for determining the feasibility of wireless power transmission for the orbiting astronomical station.

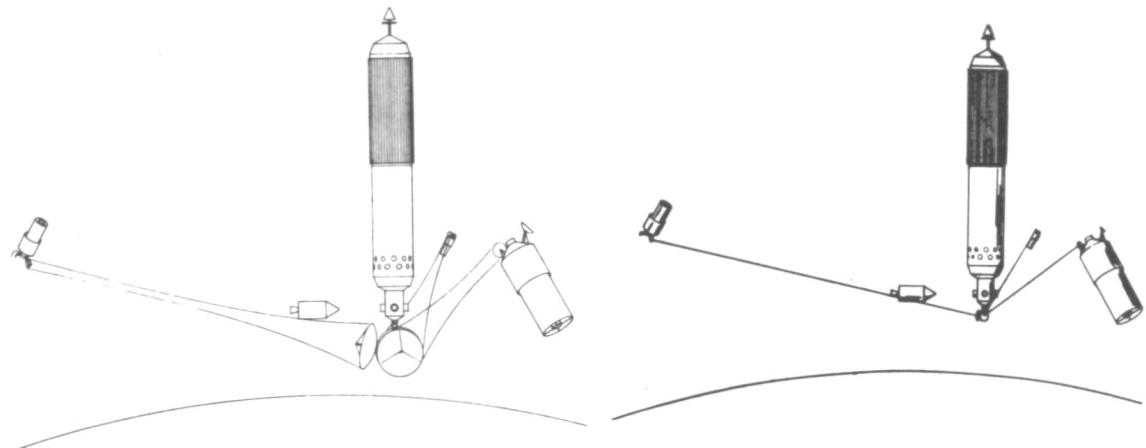


FIGURE 1. ARTIST'S CONCEPTION
OF ORBITING ASTRONOMICAL
STATION USING MICROWAVE BEAMS

FIGURE 2. ARTIST'S CONCEPTION
OF ORBITING ASTRONOMICAL
STATION USING LASER BEAMS

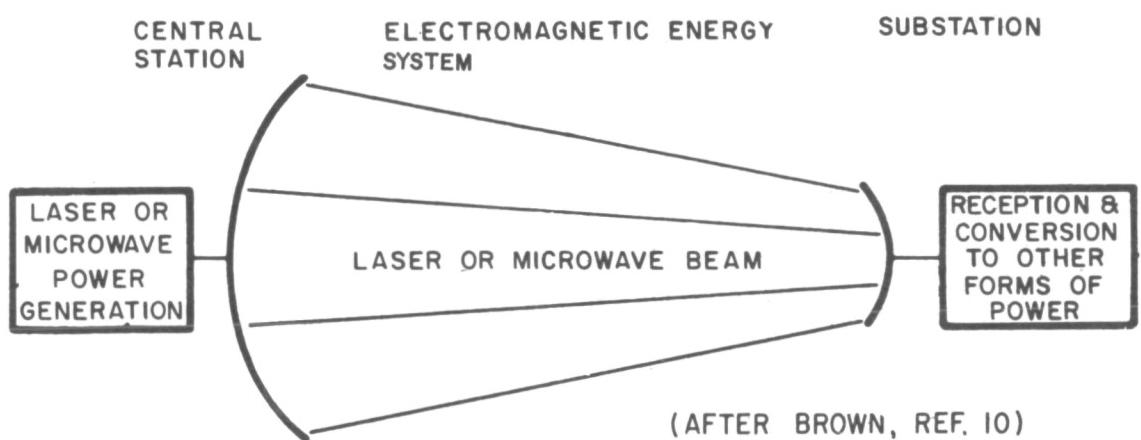


FIGURE 3. ELECTROMAGNETIC ENERGY SYSTEM

TRANSFER OF POWER BY MICROWAVES

A general outline of a microwave power transfer system is given in Figure 4, and the status of the constituent systems is discussed in the following text.

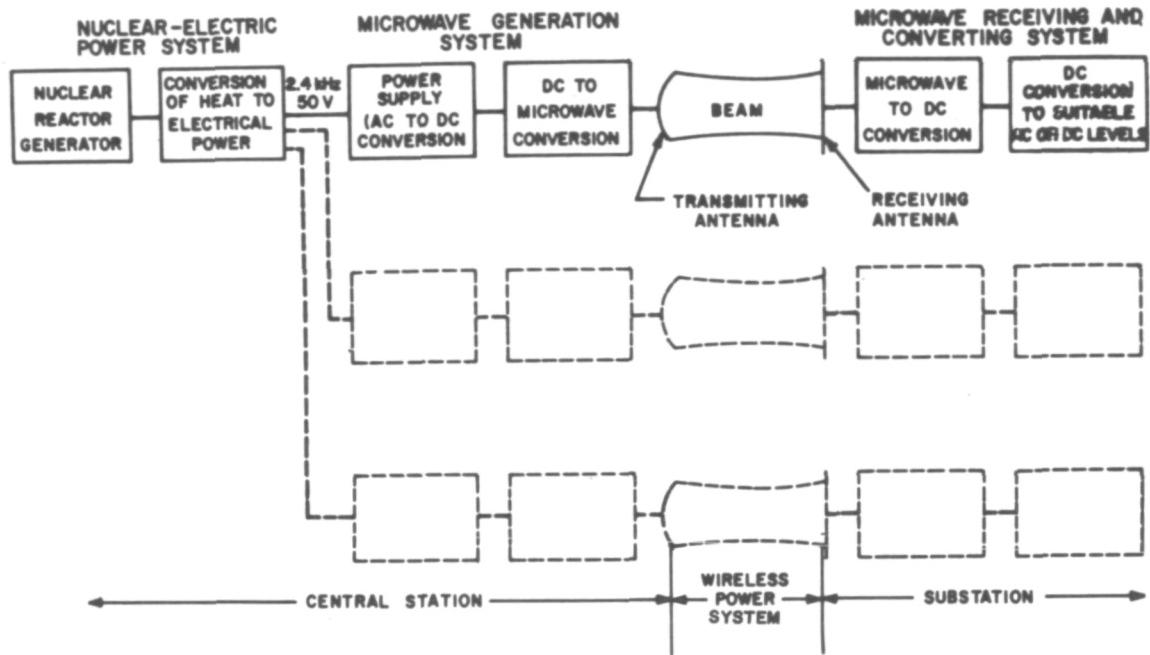


FIGURE 4. BLOCK DIAGRAM OF PROPOSED MICROWAVE POWER SYSTEM

Microwave Power Generation

Electric Power Supply Considerations. The electrical power needed for the power transmission system depends upon the overall system efficiency and varies between 21.8 percent on the basis of present experimental data to 40.5 percent for the efficiencies expected from presently available components if they were incorporated into the system in an optimum manner. (Present experimentally established efficiencies are 85 percent for the microwave generator power supply,¹ 75 percent for the dc to microwave converter, 66 percent for antenna transfer in nonoptimized systems, and 52 percent for the substation rf collector and rectifier [9]. Therefore, overall efficiency is $0.85 \times 0.75 \times 0.66$

1. Discussion with Mr. H. F. Fichtner, R-ASTR, MSFC

$\times 0.52 \approx 21.8\%$). If, however, we make use of the present state-of-the-art in component development the overall efficiency can be considerably higher and the electric power supply requirement reduced. On the other hand, there may be a tradeoff relationship between the efficiency and the size of the antennas which will result in operation at reduced efficiency.

A survey of electric-power systems in use on space vehicles shows a trend toward high frequency electrical systems as a means of reducing power loss, system weight, and component size.² Although frequencies higher than 2.4 kHz may be desirable for certain applications, this basic frequency is recommended as a practical compromise between design constraints of the nuclear power system and attempts to make optimum the capacity-to-weight ratios for electric-power equipment. High-performance materials for use at this frequency are becoming available for motors, transformers, etc., and the new equipment shows significant advantages over equipment operating at 400 Hz. Moreover, proven equipment designed for 400 Hz operation may be used, since 2.4 kHz is readily converted to three-phase 400 Hz power (using semiconductor static inverters and counting techniques for signal splitting).

An operating voltage of 50 V appears to be practical because of limitations in the speed of system rotary components and in high-temperature insulation. This voltage is acceptable for equipment now in use since semiconductor switches and other components can operate reliably at this potential. In addition, should static conversion equipment be required, this voltage would permit the use of static power modules without overstressing the components. When higher voltages are needed, they can be obtained with available high-performance, low-mass transformers.

dc Conversion to Microwaves. Efficient microwave tubes generating hundreds of kilowatts of continuous power in the microwave domain have been developed [3, 4, 7]. A scaled-down version for use in space power transmission may be adapted from one type, the Amplitron, first developed in 1955 by Raytheon Company [3, 4]. Present types of Amplitrons have demonstrated in the laboratory 400 kW output in the 10 cm band at 75 percent operating efficiency [37, 38], and the basic operating principle is such that with additional development 90 percent operating efficiency should be possible [39].

The principle of Amplitron operation is a continuous crossed-field interaction, as in the conventional magnetron oscillator. Besides having the magnetron's high efficiency and simple construction, the Amplitron is able to amplify over a broad frequency band [37, 38]. The details of its operation

2. Discussion with Mr. R. Boehme, R-ASTR, MSFC

and construction are given in References 4, 11, 12, 37, and 38, so only a brief description is given here.

The Amplitron consists of a "cold" cathode, a slow wave structure arranged concentrically around the cathode, a magnetic field through the axis of the cathode, and a dc electric field between the cathode and the slow wave structure (Fig. 5).

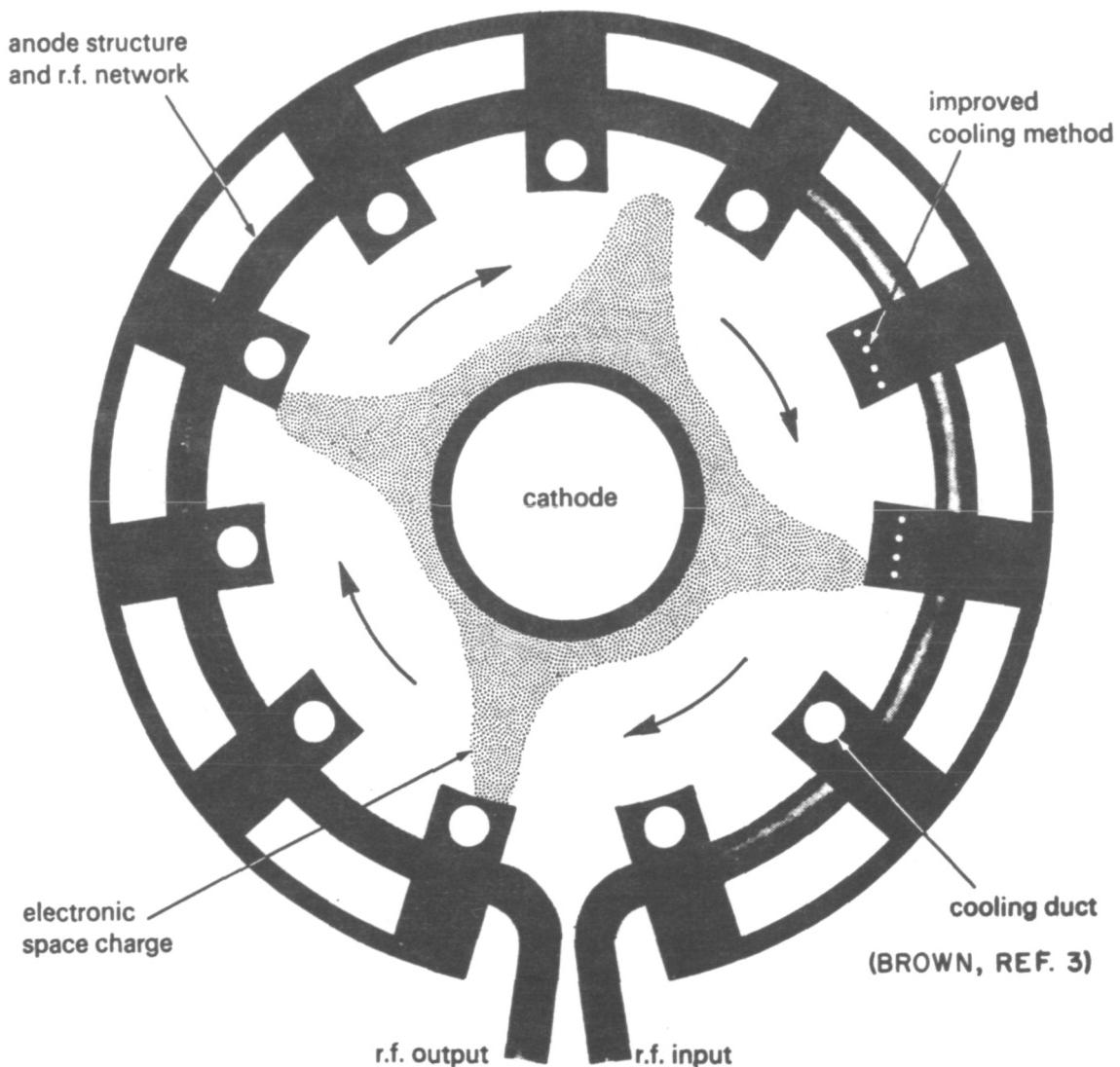


FIGURE 5. DIAGRAM OF BASIC AMPLITRON

To put the Amplitron into operation, a dc potential from an external source is applied, causing electrons to leave the cathode. Under the influence of the magnetic field, the electrons rotate in concentric circles around the cathode. When a traveling rf wave is introduced, it interacts with the rotating electrons or rotating space charge. As the dc potential is increased, a critical value is reached; the electron angular velocity is in synchronism with the rf wave fields. The electrons lose energy to the rf fields at the same rate at which they accept energy from the dc field. The power generated is proportional to the product of torque and angular velocity.

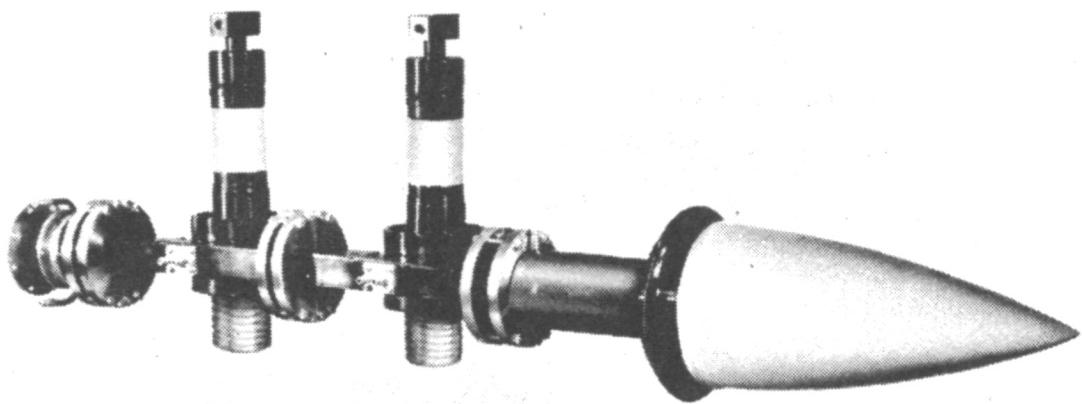
A double-stage Amplitron is illustrated in Figure 6. This cascade arrangement, producing 425 kW of continuous-wave power at a wavelength of 10 cm, radiates rf power into space directly through the radome vacuum window. The efficiency of this device as a function of output power is shown in Figure 7. A maximum efficiency of 74 percent was obtained at a power output of 400 kW and the efficiency is nearly as high at lower power levels. This tube will also operate over an appreciable bandwidth of 50 MHz at nearly constant efficiency as shown in Figure 7a. In obtaining the data of Figure 7a, the strength of the magnetic field was reduced somewhat as a safety precaution in testing the tube and this is responsible for the slightly reduced efficiency from Figure 7. The operating potential of this tube varies from 25 kilovolts for the highest efficiency to 18 kilovolts for that efficiency shown in Figure 7a.

A single-stage Amplitron, also illustrated in Figure 6, has a lower output of 50 kW, having been derated for long tube life ($\approx 10,000$ hours). Microwave power transmission in space would require a scaled-down Amplitron with about a 10 kW output for each substation. Such an Amplitron is now available and with further refinement could perhaps fulfill this specific need.

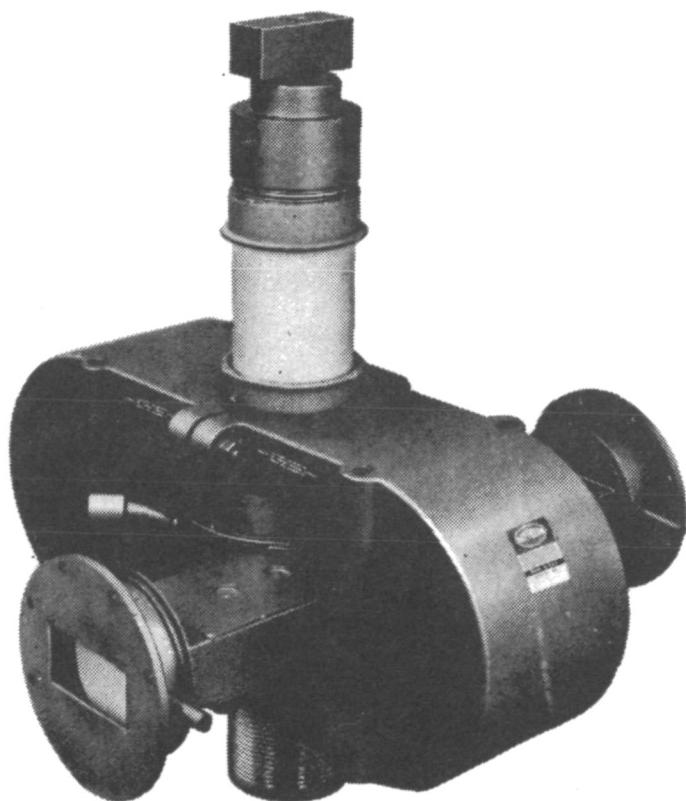
One desirable feature of the Amplitron device as distinguished from the conventional magnetron is that because it is an amplifier it can be used for information as well as for power purposes. Data rates of at least 10 megabits per second preferably in the form of frequency modulation may be handled by the device.

The optimum frequency range of the Amplitron is 1 GHz ($\lambda = 30$ cm) to 10 GHz ($\lambda = 3$ cm). The operating frequency must be considered not only in regard to optimum transmission but also with respect to potential interference with sensitive land-based radar, microwave (TV and telephone), and spacecraft telecommunication systems.

DOUBLE - STAGE (QR 849)



SINGLE - STAGE (QR 1262)



(BROWN, REF. 9)

FIGURE 6. SUPERPOWER AMPLITRONS

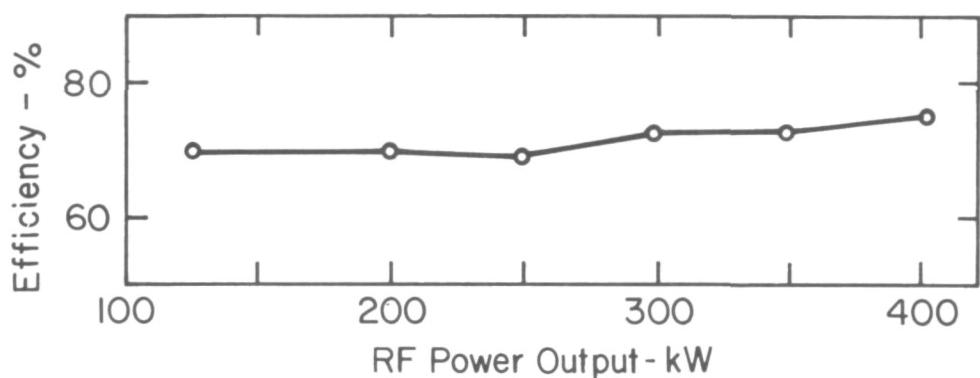


FIGURE 7. EFFICIENCY AS A FUNCTION OF CW POWER OUTPUT
FOR THE QR 849 AMPLITRON

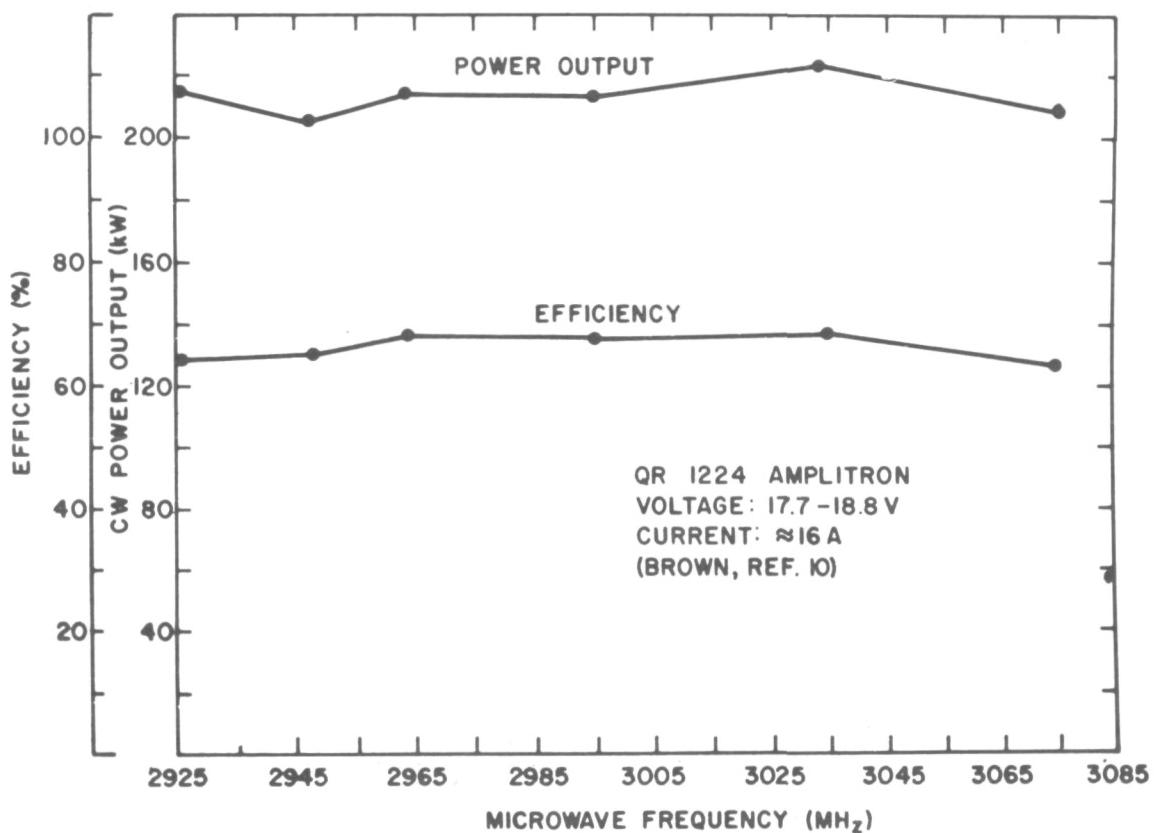


FIGURE 7a. EFFICIENCY AND POWER OUTPUT
RELATIVE TO MICROWAVE FREQUENCY

The power-supply requirement for the present high-power Amplitrons is 20 kV at 15 to 20 amperes. However, Amplitrons for a lower power level can be and have been designed without loss of any of their desirable operating features. For example, a low-power Amplitron designed to operate on a frequency of 3.035 GHz ($\lambda = 10$ cm) and having an output of 10 kW, including 3 kW for reserve, would need a power-supply input of approximately 17 kW (calculations based on 85 percent efficiency for the power supply and 70 percent for the Amplitron).

Status of Development. In Figure 8 are shown the efficiency and power outputs of single microwave generators working at a 10 cm wavelength, for the period of 1940 to 1963 [3]. Although the average rate of power increase over

this time period was 50 times per decade, it is noted that the rate of increase was low from 1950 to 1958. Then the Office of Electronics, U.S. Department of Defense, recognizing the need for higher-power devices, initiated several developmental studies in 1960. One of the objectives was to increase available power levels by several orders of magnitude. As a result of this support, by 1963 as much as 400 kW of continuous power at a 10 cm wavelength could be generated. This was 200 times the maximum available in 1948 and 20 times the amount available three years earlier.

Microwave power of a few hundred watts was transmitted at 2450 MHz over a distance of 7.6 m (25 ft) in an experiment by Raytheon [2, 10]. In this experiment 400 watts of microwave power from a magnetron was transferred from the transmitting antenna to the receiving antenna and its waveguide load with an efficiency of 50.5 percent. The rf power was then rectified in a close spaced thermionic diode with an efficiency of 50 percent to produce a dc output of 100 watts. The use of an amplitron of 70 percent would provide an overall dc to dc transfer efficiency of 18 percent.

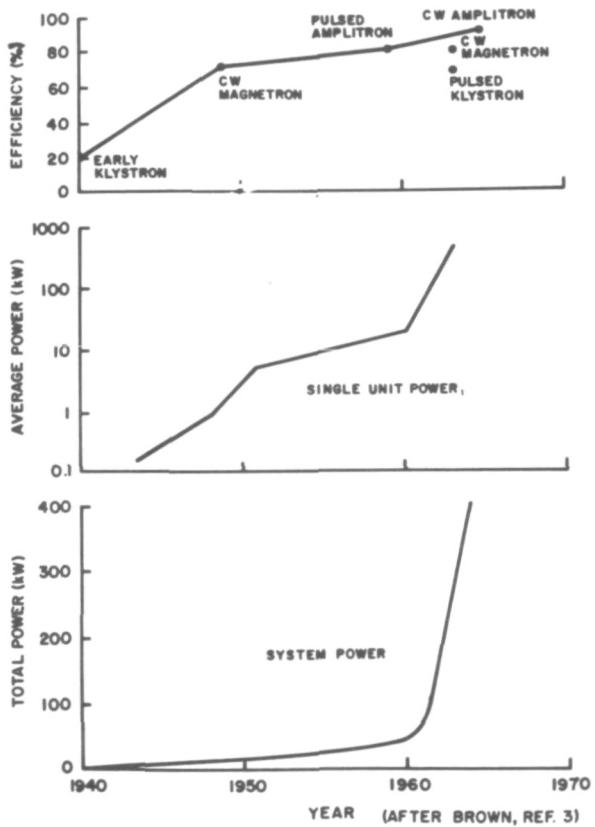


FIGURE 8. DEVELOPMENT OF EFFICIENCY AND POWER OUTPUT OF MICROWAVE GENERATORS WORKING AT A 10-cm WAVELENGTH

In 1964, Rome Air Development Center, Griffiss Air Force Base, supported a feasibility study for the construction of a microwave-powered helicopter device. A successful demonstration was made by Raytheon in October 1964 [2, 15], when a 2.3 kg (5 lbm) tether-guided helicopter with an excess lift of 0.7 kg (1.5 lbm) at sea level was kept aloft at 15.2 m (50 ft) for 10 hours. The helicopter (Fig. 9) had a rotor diameter of 1.8 m (6 ft), and was powered by a 0.1 kW (0.15 hp) electric motor that received its power from a rectenna (rectifier-antenna). The rectenna (Fig. 10), receiving microwaves at a frequency of 2450 MHz from a ground-based transmitter, was an array of diodes covering an area of 3700 sq cm (4 sq ft); its dc output was 230 W.

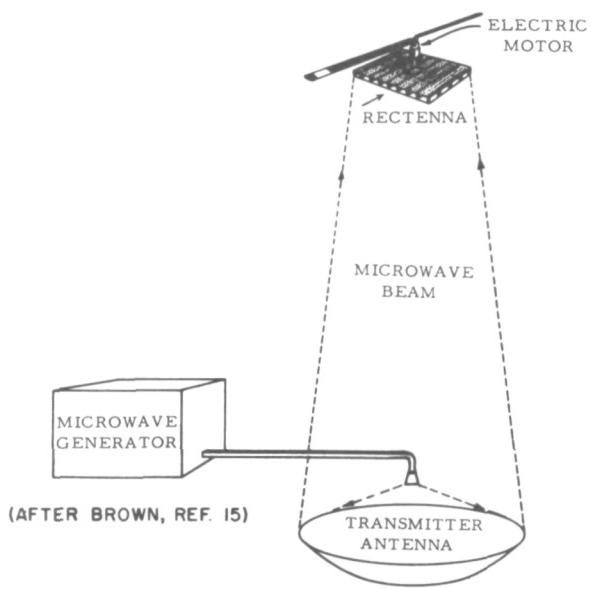


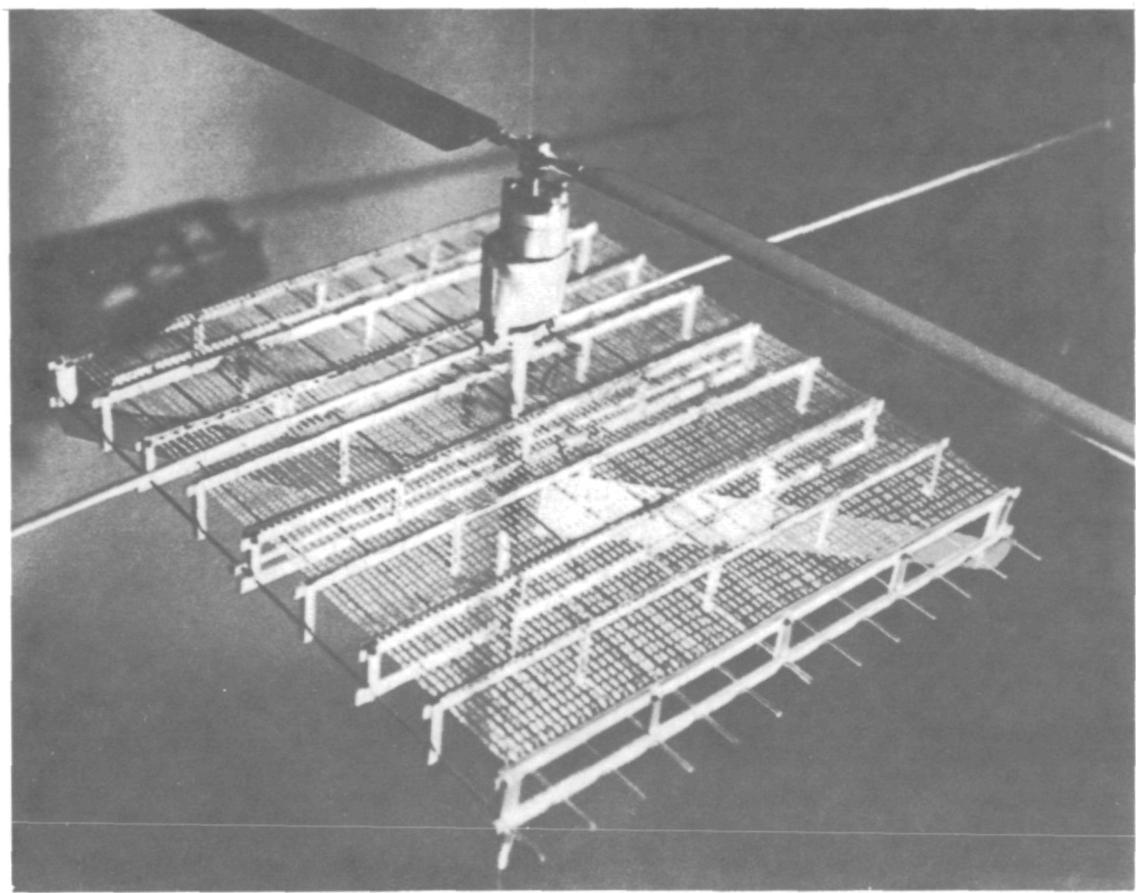
FIGURE 9. DIAGRAM OF
MICROWAVE-POWERED
HELICOPTER DEMONSTRATION

successfully developed beam-riding technique could be applied to the stabilization of an astronomical substation position with respect to the central station (except for control of the separation distance). The facts that microwave power has been transmitted and converted to electricity to power a helicopter device, and that work is under way for similar power transmission at greater distances, with the addition of guidance and control, all support the feasibility of microwave power transmission between the astronomical satellites.

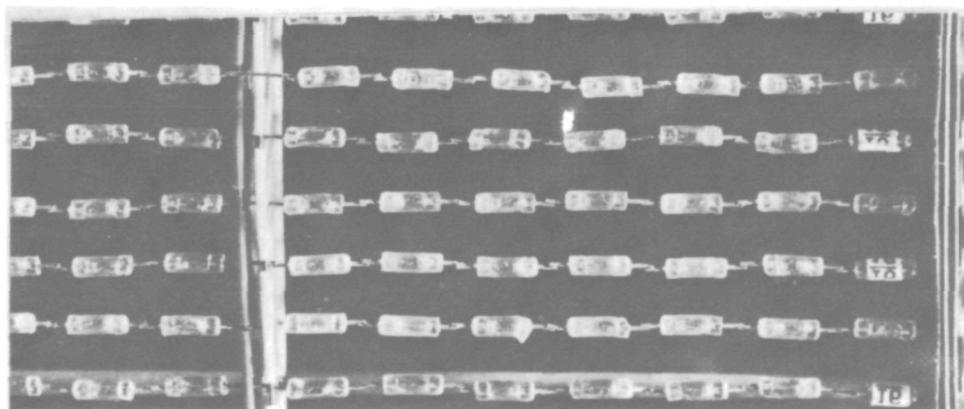
In 1968, under a second contract from the Rome Air Development Center, work was successfully completed on a beam-riding system for a helicopter in which the tether wires were eliminated [16, 15, 40]. In this project, the microwave beam was used as a reference for determining helicopter position in five degrees of freedom (pitch, roll, yaw, and X and Y translation).

Raytheon Company has also proposed an airborne vehicle of this type for applications such as a surveillance or communications platform to fly above the cloud cover up to an altitude of 15.2 km (50 000 ft).

The work on a beam-riding system and the proposal for its application to a distant flying platform are relevant to the requirements for attitude control of an orbiting astronomical station. A



DETAIL OF RECTENNA DIODE ARRAY



(BROWN, REF. 3)

FIGURE 10. EXPERIMENTAL HELICOPTER

Special Engineering Considerations. Special considerations in the application of the microwave generator system relate to (1) heat generated within the power supplies and generator device,³ and to (2) the possibility of electromagnetic interference with other services because of the high powers transmitted.

The selected frequency of operation would have to be determined through agreement with the Department of Defense, NASA, and FCC agencies to prevent interference with sensitive land-based radar systems, microwave TV and telephone systems, and spacecraft-to-Earth data links.

The present method of cooling a microwave amplifier is through water circulation. The heat removed could be radiated into space by means of heat pipes [17, 18], or could be used to warm the crew living quarters. The amount of heat to be removed is calculated on the basis of generator system efficiencies and residual power needs. Thus, with the assumption of 70 percent efficiency for the Amplitron or other microwave amplifier, 85 percent efficiency for the power supply, a 17 kW power-supply input, and about a 10 kW useful microwave output, approximately 7 kW of heat would have to be removed.

Microwave Power Transmission

Microwave power transmission to a satellite substation at a known distance from the central station will require better transfer efficiency than is obtained in present radar and communication systems. The Raytheon Company has performed extensive experimental work in the area of efficient power transmission, and has achieved an efficiency of 52 percent as measured by the ratio of power output in the receiving horn waveguide to the power in the waveguide that feeds the transmitting horn. It has also pioneered in the generation of a gaussian microwave beam that has a desired set of properties such that the beam can be used as a position reference to control a vehicle in five of the six degrees of freedom available to a space vehicle. Further, the gaussian beam is capable of transfer efficiencies that are at least as good as the more conventional approach that has been experimentally evaluated. Finally, Raytheon has also developed a new device that combines the functions of the receiving antenna and the rf to dc converter and which in doing so results in an efficient element with desirable non-directional properties. This latter element is described under Microwave Power Reception and Conversion.

Stated most simply, power transmission by microwave beam is a matter of generating as narrow or sharp a beam as possible so that the receiving antenna

3. Discussions with Mr. W. Snoddy and Mr. A. Byrd, R-SSL, MSFC

can intercept most of the beam. To a close approximation the sharpness of this beam is controlled by the ratio of the diameter of the transmitting aperture to the wavelength of the radiation being employed. It is affected to a small degree by the distribution of illumination intensity over the aperture. There does not appear to be any way in which we can significantly trade off aperture size for some other element, other than wavelength, of course. However, the type of transmitting antenna that is used and the illumination of the antenna aperture may be of considerable importance when we are involved with obtaining the highest transmission efficiency and in utilizing the beam for guidance as well as power transmission purposes.

The classic means by which a beam is formed is the uniform illumination of an aperture with a plane wave phase front. This stems, of course, from the classical experiments in optics in which an aperture can be easily illuminated in this manner. If such an aperture is so illuminated, either by microwaves or light, and we examine the distribution of energy in a plane parallel to the aperture at various distances from the aperture, it is found that close to the transmitting aperture in the so-called Fresnel region, the energy distribution across the wave front may vary rapidly with distance from the antenna. On the other hand, in the Fraunhofer, or far field region, there is a fixed pattern of a main lobe with 84 percent of the energy contained within that lobe, and a series of side lobes.

This type of illumination would correspond to the uniform illumination of a parabolic reflector. A more generalized approach to the illumination of the aperture would be with a non-plane wavefront which would correspond to the type of illumination pattern we would obtain from an ellipsoidal reflector. In the general case of the ellipsoidal reflector we can bring the far field or Fraunhofer region into the other focal point of the ellipsoidal geometry. Then, depending upon the parameters of the ellipse, this second focal point can be brought in to an arbitrary distance from the transmitting aperture. This approach has been examined experimentally for power transfer efficiency and, therefore, deserves further discussion.

Consider the configuration of an ellipsoid of revolution for the antenna system. In this arrangement, the transmitting antenna is at one apsis of the ellipsoid, the propagation source is at a focal point, and the detector at the other focal point. The basis for this configuration is the principle in which all energy waves emanating from a transmission focal point will traverse the same distance to the receiving focal point, and all energy waves radiated in phase will arrive in phase. The energy waves also will be in phase in a spherical

surface having its center at the receiving focal point. This is illustrated in Figure 11, which shows the outer edge of the spherical surface coinciding with the aperture of the ellipsoidal antenna used as a reflecting surface.

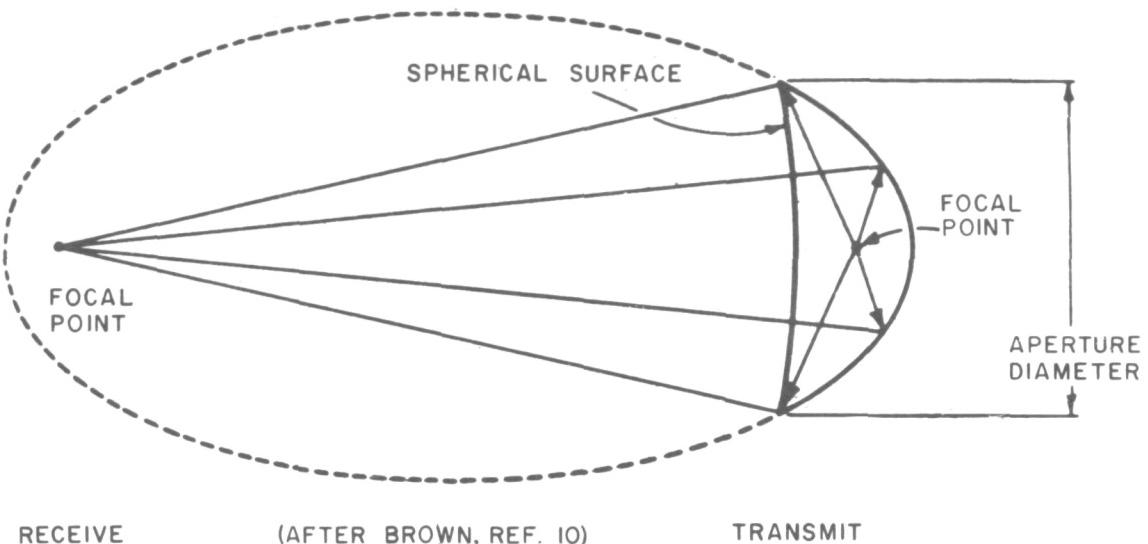
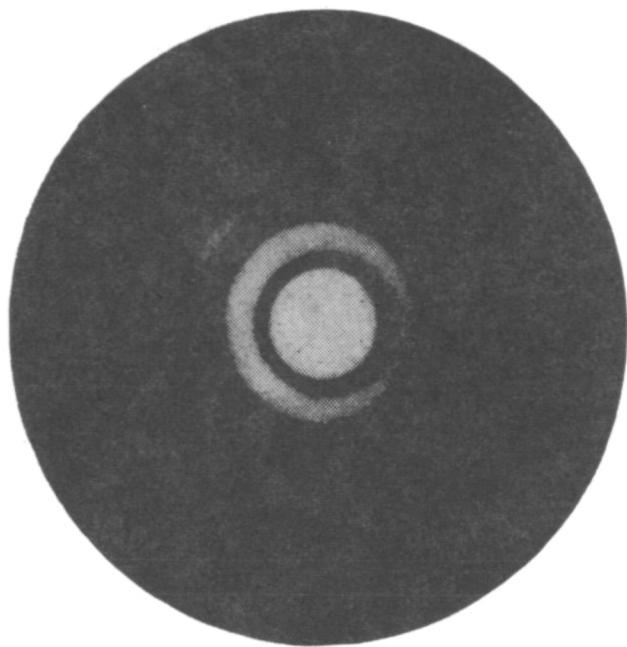


FIGURE 11. POWER TRANSFER IN AN ELLIPSOIDAL CONFIGURATION

In practice, because of energy diffraction, not all the radiated energy will converge at the receiving focal point. Instead, the energy will have a distribution about this focal point, determined by the wavelength, the diameter of the transmitting aperture, and the distance between the focal points. This energy distribution will follow a Fraunhofer diffraction pattern (illustrated in Fig. 12). Mathematically, the distribution is a Bessel function; the use of this relationship is discussed in the next subdivision, Microwave Power Reception and Conversion.

An ellipsoidal reflector was used in an experiment shown in Figure 12a to verify this theoretical power-distribution pattern. The results of the experiment are compared with a theoretical power distribution in Figure 13, which shows the close correlation of theory with experimental data. In this experiment, in which an operating wavelength of 8.2 mm was used, the overall power-transfer efficiency was $52\text{ percent} \pm 2\text{ percent}$. (The individual component efficiencies are stated in Reference 10, in which the experiment is discussed in detail.)



(BORN & WOLF, REF. 25)

FIGURE 12. FRAUNHOFER LIGHT-DIFFRACTION PATTERN

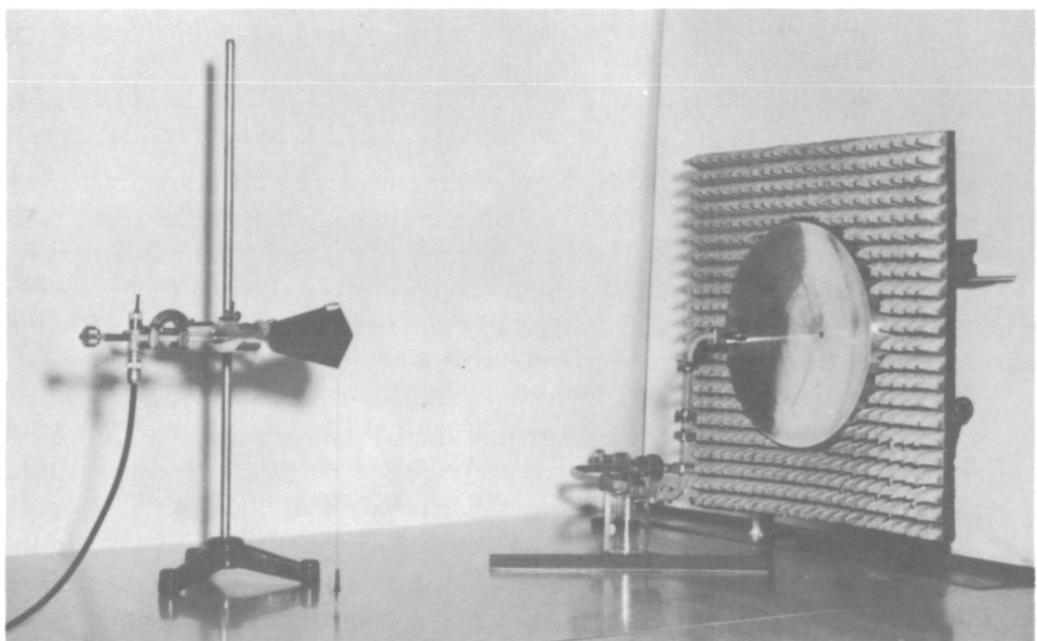


FIGURE 12a. LABORATORY EXPERIMENT FOR THE EFFICIENT TRANSMISSION OF ELECTROMAGNETIC RADIATION AT A WAVELENGTH OF 8.2 MILLIMETERS
(A waveguide to waveguide efficiency of 52 percent was obtained.)

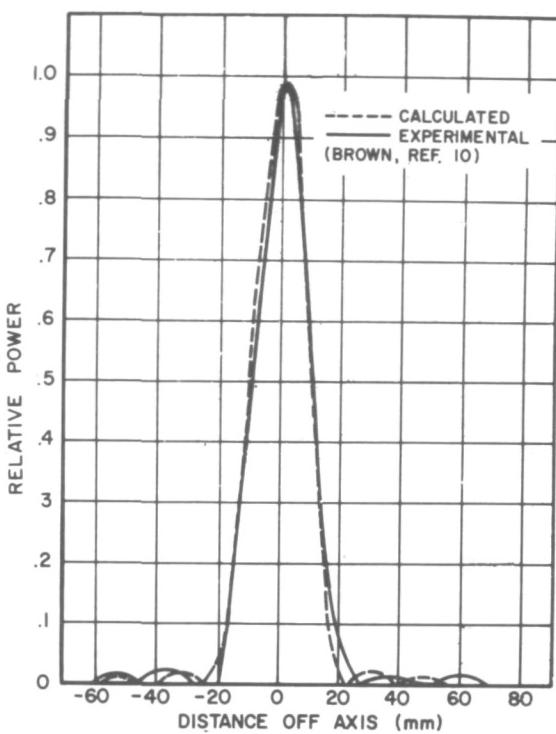


FIGURE 13. COMPARISON OF EXPERIMENTAL AND CALCULATED POWER DISTRIBUTIONS

Information on microwave energy transfer at a proposed settlement on the Moon has been estimated [8]. This information is presented in Table I, which shows how the diameter of the antenna and the mass of the antenna, transmitter, and receiver would vary as a function of distance of power transfer and radiation wavelength. The transmitting and receiving antennas are the same size for these estimates, and the power transfer is between an unshielded nuclear-power source and a distant central station. For power transfer between the central station and outposts which may have to be shifted at times, it was suggested that the main center have a large antenna and the receiving sites have small ones, possibly a few feet in diameter and with a mass of half a kilogram (1 lbm).

In a related study of microwave power transfer (a microwave-powered helicopter to be used as a communication platform 1 to 2 miles above the Earth's surface) [16, 19], information has been developed on factors of cost, size, and

The following calculations have been made for a hypothetical example of microwave power transfer in an ellipsoidal configuration. When the wavelength is 10 cm, a transmitter antenna diameter of 122 m (400 ft) is needed to project 84 percent of the microwave power 16 km (10 miles) to a receiving antenna with a 30.5 m (100 ft) diameter. This is illustrated in Figure 14.

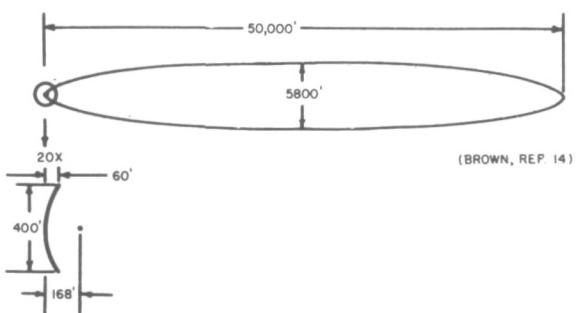


FIGURE 14. DIMENSIONS OF ELLIPSE IN HYPOTHETICAL MICROWAVE POWER TRANSFER

TABLE I. ESTIMATED MASS OF COMPLETE MICROWAVE ENERGY TRANSFER SYSTEMS*

Distance of Power Transfer km (mi)	Power Level (kW)	Wavelength of Radiation (cm)	Antenna Diameter ** m (ft)	Transmitter Mass kg (lbm)	Antenna Mass kg (lbm)	Receiver Mass kg (lbm)	Total Mass kg (lbm)
1.6 (1)	35	10	15.2 (50)	31.8 (70)	90.7 (200)	15.9 (35)	138.4 (305)
	3	3	9.1 (30)	31.8	22.7 (50)	15.9	70.4 (155)
100	1	1	4.9 (16)	31.8	4.5 (10)	15.9	52.2 (115)
	10	10	15.2	90.7 (200)	90.7	45.4 (100)	226.8 (500)
1000	3	3	9.1	90.7	22.7	45.4	158.8 (350)
	1	1	4.9	90.7	4.5	45.4	140.6 (310)
16 (10)	10	10	15.2	680.4 (1500)	90.7	454 (1000)	1225.1 (2700)
	3	3	9.1	680.4	22.7	454	1157.1 (2550)
10000	1	1	4.9	680.4	4.5	454	1138.9 (2510)
	10	10	45.7	31.8	2449.4 (5400)	15.9	2497.1 (5505)
100000	3	3	27.4	31.8	616.9 (1360)	15.9	664.6 (1465)
	10	10	15.2	31.8	90.7	15.9	138.4
1000000	1	1	15.2	90.7	2449.4	45.4	2585.5 (5700)
	10	10	45.7	90.7	616.9	45.4	753.0 (1660)
10000000	3	3	27.4	90.7	90.7	45.4	226.8
	10	10	45.7	680.4	2449.4	454	3583.8 (7900)
100000000	3	3	27.4	680.4	616.9	454	1751.3 (3860)
	1	1	15.2	680.4	90.7	454	1225.1

* Data after Brown [8]

** Antenna Diameter based on 75% capture efficiency

weight. This information is applicable to the present conception of an astronomical station since considerations of distances, power levels, equipment, and antennas apply to both. Wavelength is an important parameter in both applications. As the wavelength is reduced, antenna size and cost decrease. However, reliability of components and efficiency of microwave power sources and rectifiers also decrease, but the cost does not diminish proportionally.

In introducing the second approach to generating a microwave beam, it is noted that there is one special type of illumination of the transmitting aperture that will result in a beam which has the same distribution pattern of energy along any plane parallel to that of the aperture [34], regardless of the distance of that plane from the aperture. In other words, for this case there is neither a far field nor a near field pattern. This type of beam which is brought about by a gaussian illumination distribution of the aperture is called a gaussian beam. The gaussian beam is the only type of beam that will provide a suitable distribution for the beam-riding microwave sensors for docking applications in which it is desired to use the microwave beam as a position reference at all distances measured from the face of the antenna [28, 40].

The gaussian beam is quite frequently used in lasers because of the ease with which it is generated by the use of two confocal mirrors [33]. The problem is more difficult with microwaves, but one approach developed and used successfully at Raytheon seems straightforward. This approach was a modified confocal resonator cavity that couples to space through a coupling plate, which forms the face of the antenna. This approach is shown in Figure 14a. Such a distribution, however, could be established by other means, most notably by that of a phase array.

The essential features of a gaussian beam are shown in Figure 14b. The intensity distribution at any cross-section is gaussian. The beam converges, reaches a minimum size, and diverges again. There is a region near minimum size where the beam intensity changes slowly with distance. The wavefronts are nearly spherical. The field pattern is almost TEM. The beam width is approximately the same in the plane of polarization and at right angles to it. Beams of this type differ in essentially one parameter, which is the ratio of wavelength to minimum beam cross-section.

A gaussian beam distribution is defined as

$$E = E_0 e^{- (r/\omega)^2}$$

where E_0 is the value of the field at the axis and is a function of the distance z .

Referring to Figure 14b, it will be noted that ω is the value of r at which the field intensity E is E_0/e . At the waist of the gaussian beam, the value of r at which the field intensity is E_0/e is denoted by ω_0 .

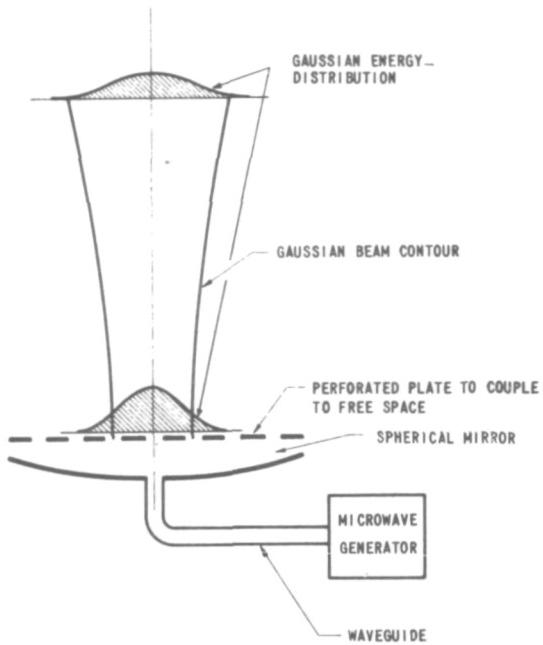


FIGURE 14a. SCHEMATIC OF GAUSSIAN ANTENNA

The relationship between z , ω , ω_0 , and the microwave wavelength λ is as follows:

$$\omega^2(z) = \omega_0^2 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2} \right)^2 \right]$$

The beam contour $\omega(z)$ is a hyperbola with asymptotes inclined to the axis at an angle

$$\theta = \frac{\lambda}{\pi \omega_0}$$

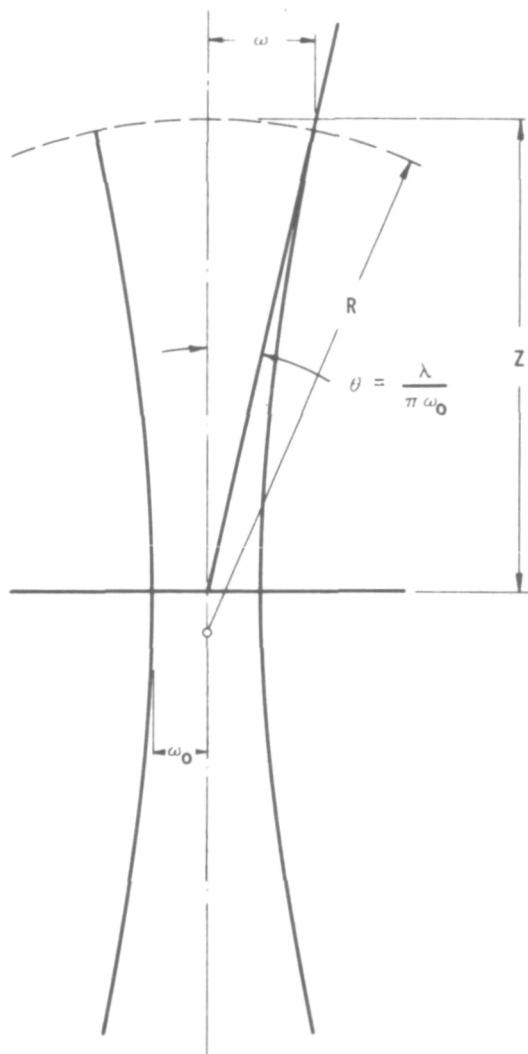


FIGURE 14b. SCHEMATIC OF GAUSSIAN BEAM

This is the far field diffraction angle of the fundamental mode.

As indicated in Figure 14b, R is the radius of curvature of the wavefront. The radius of curvature R as a function of z is given by

$$R(z) = Z \left[1 + \left(\frac{\pi \omega_0^2}{\lambda z} \right)^2 \right]$$

The equation $E = E_0 e^{-\frac{(r/\omega)^2}{2}}$ indicates the field intensity as a function of the radius r. It is found by squaring and integrating this equation that the power contained within a circle determined by $r = \omega$ is 86.5 percent of the total power in the cross-section. More generally the percentage of the total power which is contained within a given circle of radius r is shown in Figure 14c. It will be noted from this graph that the efficiency of collection beyond 86.5 percent can be increased only by a substantial increase in the total area of the collecting aperture.

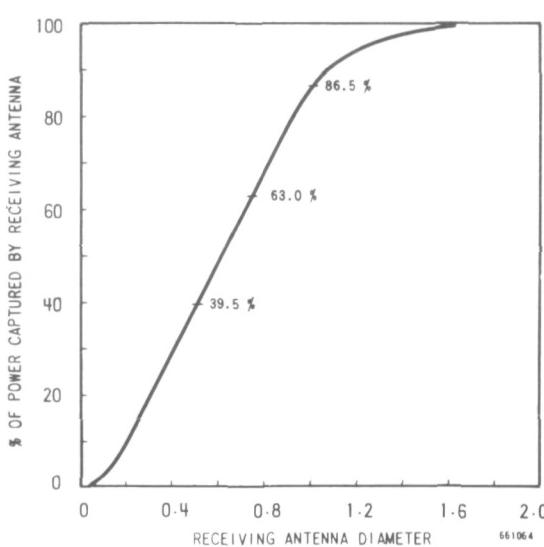


FIGURE 14c. PERCENT OF TOTAL ac POWER IN GAUSSIAN BEAM (which passes through a diameter D_r normalized so that $D_r/2\omega = 1$, where 2ω is diameter at which power density is $1/e$ that on axis).

It is of some interest to note that the gaussian beam need not be generated at the face of the antenna aperture as a plane wave. Rather, by using a concave aperture with a suitable modification of the resonant cavity, the beam can be made to converge before it diverges.

There is a practical interest in using such a beam in that it is found that with a given transmitter aperture size and a given separation between the transmitting and receiving apertures the use of an optimum convergent beam will reduce the area of the receiving aperture needed for 86.5 percent transfer efficiency by a factor of 2 over a plane wave illumination of the transmitter aperture. It is further found that the convergent beam is optimized when the waist of the beam is midway between the transmitting and receiving apertures

and the diameter of the waist ω_0 is equal to 70 percent of the diameter of ω at the transmitting and receiving apertures.

It may be of additional interest to attempt to compare aperture sizes for the uniformly illuminated aperture and the gaussian illuminated aperture. It is noted that for the case of plane wave illumination of the aperture the far field angle between the first nulls (84 percent transmission efficiency) for the uniformly illuminated aperture is $2.4\lambda/d$, while for the gaussian illumination the far field angle between $\pm\omega$ (86.5 percent transmission efficiency) is $2\lambda/\pi\omega_0$.

This indicates an advantage in far field angles of 1.9 in favor of the gaussian beam. However, this is misleading in that the actual physical dimensions of the transmitting aperture must be larger than ω_0 . How much larger has not been investigated fully and would undoubtedly involve the degree to which the beam could depart from being pure gaussian and still be suitable for beam guidance purposes. In the experimental work which has been done at the Raytheon Company the physical aperture has been approximately 1.8 times that diameter corresponding to ω_0 [28].

Of course, it has also been indicated that the gaussian beam phase front can be made convergent at the transmitter aperture to reduce the spot size at the receiving aperture. However, the phase front of the uniform illumination of an aperture could also be made convergent and that might reduce the spot size at the receiving point also. It must also be noted that the power density levels near the null points of the far field pattern of the uniform illumination case are so insignificant that the diameter of the receiving antenna can be significantly reduced in diameter without significantly influencing the efficiency of transfer while this is not the situation in the gaussian beam case.

One of the factors in the overall transmission efficiency is the efficiency of illumination of the aperture. Illumination efficiencies of standard radar and communication apertures are typically 70 percent. Higher efficiencies can be achieved with horn type or lens type apertures, but these are very bulky. Phased arrays also provide high illumination efficiency and are not necessarily bulky, but present methods of construction are complex. The gaussian beam transmitter as shown in Figure 14a may be capable of high efficiency with improvements of the coupling of microwave energy into the cavity from the microwave generator.

Microwave Power Reception and Conversion

Receiving Antennas. The transmitting-antenna diameter, wavelength, and the distance to the receiving antenna are the critical parameters that determine the receiving-antenna diameter at the substation. We get some idea of the antenna sizes by using the equation that describes the distance across the central bright disk in the Fraunhofer diffraction pattern (Fig. 12).

The equation for receiving antenna diameter is determined from the relationship $r_n = 1.22\lambda h/D_t$, the terms of which are shown in Figure 15. The bright central disk of the Fraunhofer diffraction pattern represents 84 percent of the transmitted energy. Since r_n is the radius of this central disk, $2r_n$, the diameter of the disk, represents the diameter of the receiving aperture D_r . The applicable equation, therefore, is:

$$2r_n = D_r = 2.44\lambda h/D_t ,$$

where h is the distance between the transmitting and receiving antennas.

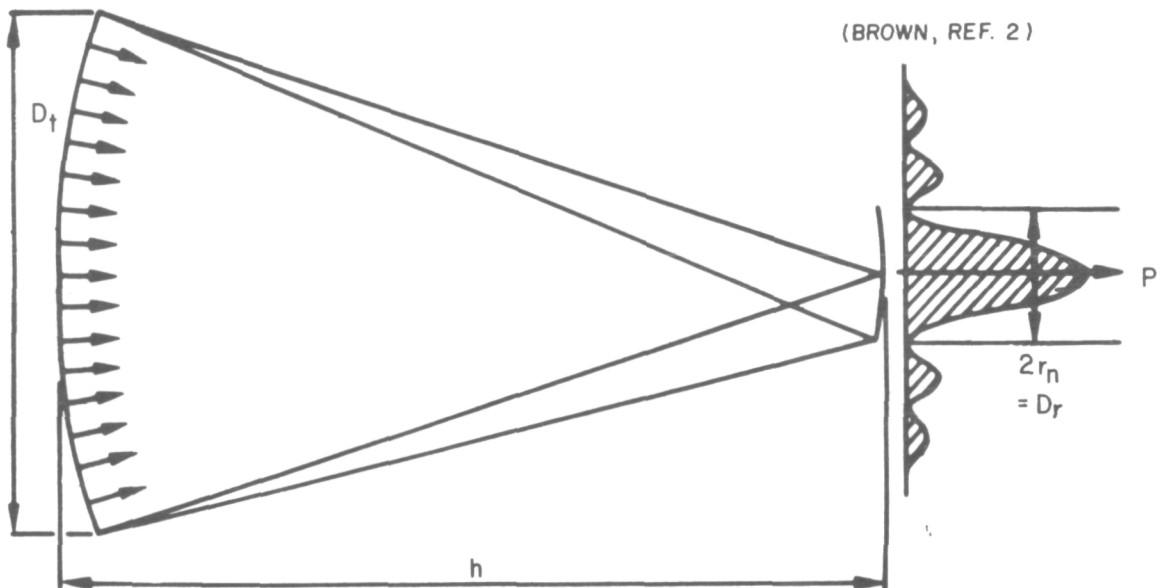


FIGURE 15. ENERGY DISTRIBUTION AS A BESSEL FUNCTION

The family of curves (Fig. 16) derived from this equation shows calculated antenna diameters for values of λ suitable for efficient Amplitron operation (10 cm - 3 cm), and for values of h representing the distance between the central station and substation (1 km - 5 km).

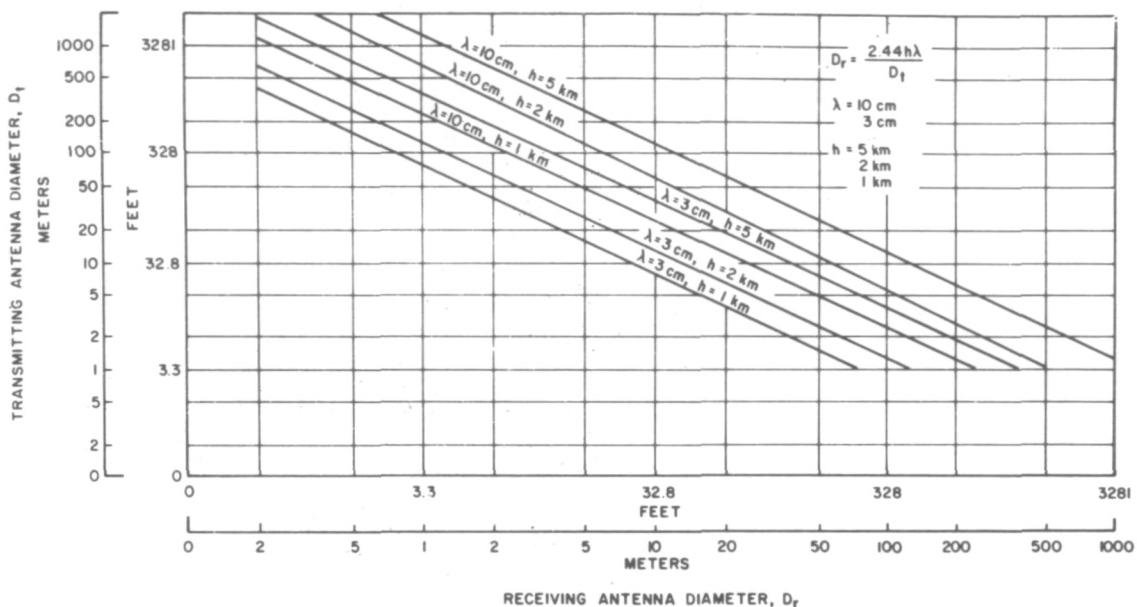


FIGURE 16. CALCULATED ANTENNA DIAMETERS
FOR THREE SEPARATION DISTANCES AND TWO MICROWAVE WAVELENGTHS

Conversion of Microwave Power to Electric Power. The development of high-power microwave generators made transfer of electrical power by microwave much more attractive as a potential method of wireless power transfer. In early considerations of power transfer, it was proposed that microwave energy be converted into heat, then to electricity. It was known that the best overall efficiency of this indirect conversion method was less than 25 percent. The need for direct conversion resulted in a number of investigations. Several of the microwave rectifiers investigated appeared promising, such as the semiconductor diodes and close-spaced thermionic diodes. Data on these and others such as klystrons, traveling-wave tubes, and various types of diodes are shown in Table II, in which the power outputs and efficiencies are compared. The injected-beam crossed-field device, with a relatively high efficiency of 42 percent for a 162 W output, does not seem suitable for aerospace applications because it is too heavy and its output impedance is too high for matching to the impedance of electric motors. On the other hand, the point-contact semiconductor diodes and the thermionic diodes are well suited to aerospace applications.

TABLE II. COMPARISON OF POWER OUTPUT AND
EFFICIENCY OF MICROWAVE RECTIFIERS*

Class	Subclass	Maximum Experimental Efficiency (%)	Maximum Experimental Power (watts)	Frequency Band
Colinear Beam	TWT	-----	-----	-----
Colinear Beam	Klystron	-----	-----	-----
Crossed-Field	Injected Beam	42	162	S
Crossed-Field	Magnetron	22	25 000 (peak)	L
Crossed-Field	Cyclotron	12	12 000 (peak)	L
Diode	Multipactor	-----	-----	-----
Diode	Thermionic	55	900	S
Diode	Point Contact Semiconductor	70	0.1	S

* Unpublished data from Brown

Their special advantages are an ability to operate continuously, an output impedance compatible with that of electric motors, and a high power-handling capability relative to their weight. The last feature it not contradicted by the low power-handling capability of single diodes (50 to 100 mW), since these are easily combined to form modules that handle a considerable amount of microwave power. For example, a method was devised for mounting standard subminiature diodes (type IN 830) in series-parallel to form a single-phase full-wave rectifier [35]. The efficiencies and outputs of this array, at 2440 MHz, are summarized as follows:

Efficiency (%)	Power Output (W)	Operating Voltage (V)
70	9.0	24
65	18.7	30
60	25.2	32 - 36

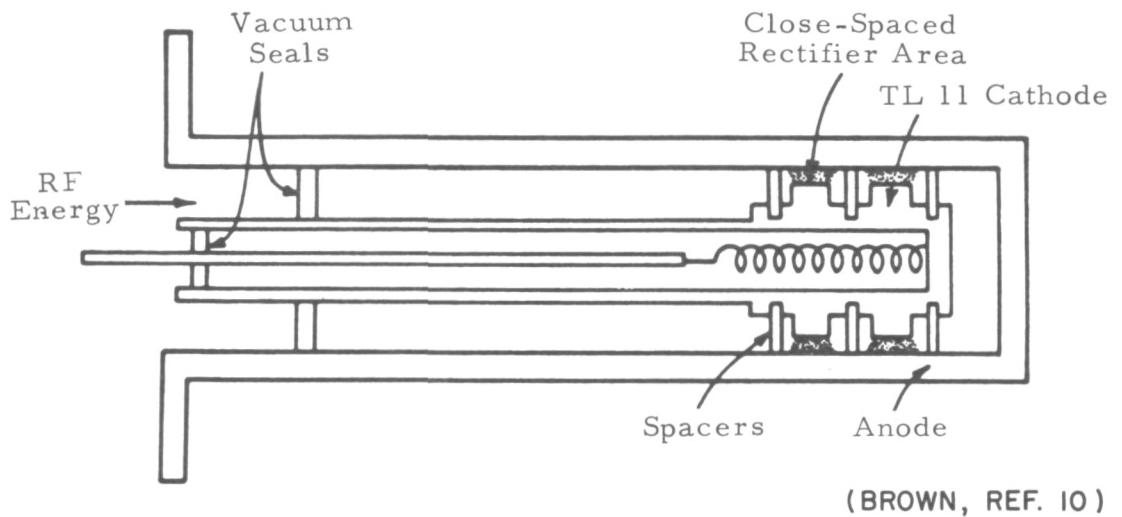
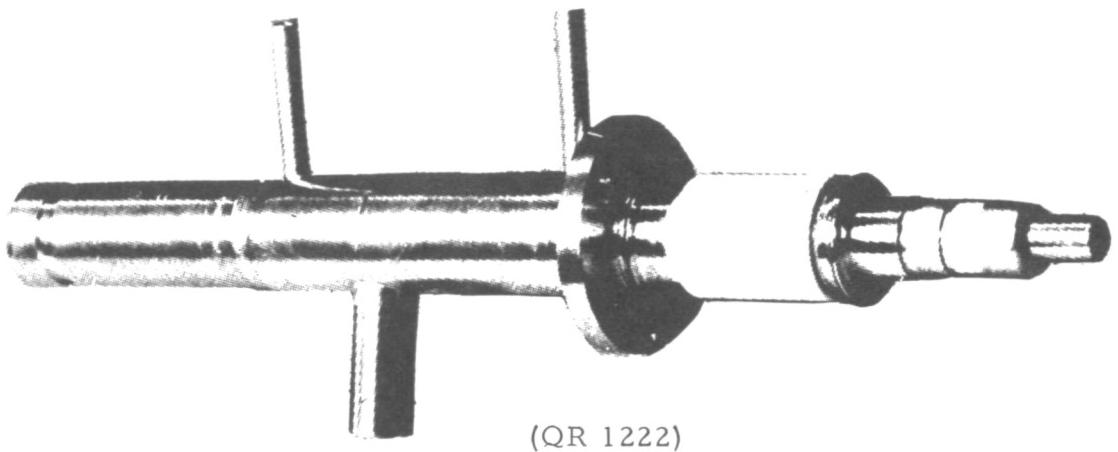
The ratio of power-handling to mass of the diode array is 250 W/0.45 kg for Sylvania IN 830 and Japan Radio IN 82G point-contact diodes. Much better power-to-mass ratios have been obtained with Schottky barrier diodes [35]. These operate typically with efficiencies of 80 percent and 200 mW output. If these diodes were arranged in a comparable array, the ratio would be 3000 W/0.45 kg.

The close-spaced thermionic diode rectifier still under study at Spencer Laboratory [10], is the highest power microwave rectifier developed. Handling microwaves at a frequency of 2450 MHz, it has produced up to 900 W of dc power at 55 percent efficiency. The QR 1222 close-spaced thermionic diode rectifier is illustrated in Figure 17.

More recently great improvements have been made in the "rectenna," a device that collects as well as rectifies the microwave energy. It has a number of properties ideally suited for space applications and will be discussed in the next section.

Properties and Status of the Rectenna. A number of different approaches to the reception of the microwave energy and its conversion into dc power have been discussed in the previous section. However, there is one approach which both in terms of advantages for aerospace application and in terms of state of development is far ahead of any other approach. This particular approach combines the receiving antenna with solid-state rectifier diodes in such a manner that (1) the energy is captured and rectified at high overall efficiencies of 70 percent or better, (2) the large aperture is comparatively non-directive so that it does not have to be pointed accurately in the direction of the transmitter, and (3) it handles its own dissipation through radiative cooling processes. This device is termed the "rectenna," combining portions of the words "rectifier" and "antenna."

The rectenna was conceived and developed [7, 29, 30, 35] after the more conventional approach of a large collecting dish and a single rectifier tube was



(BROWN, REF. 10)

FIGURE 17. CLOSE-SPACED THERMIONIC DIODE RECTIFIER

found deficient for aerospace applications. Further, although there are a large number of conceivable approaches for an efficient microwave rectifier, only one of these, the close-spaced thermionic diode rectifier, has been developed to any extent and it has a number of disadvantages when operated at short wavelengths and in an aerospace environment. Hence, the conventional approach is ruled out not only because of the high directivity of the receiving system, but because no satisfactory rectifiers have as yet been developed for the conventional approach.

The rectenna approach to the capture and rectification of microwave energy has reached a comparatively high level of development and efficiency in what can be termed the "rigid" configuration. Such a section of rigid rectenna is shown in Figure 17a. This rectenna weighs 20 grams and is capable of producing 20 watts of rectified power output. It was designed primarily for a helicopter-type application in which there is a downwash of air across the diodes for cooling purposes. However, it could be derated for space applications and adequately cooled by radiative processes.

From a historical point of view the rectenna was originally visualized as being flexible. However, the early configuration of the solid-state diodes that were available did not lend themselves to a flexible rectenna configuration. Moreover, early rectenna development centered around the helicopter for which the rigid rectenna is probably the preferred approach. Comparatively recently, however, the interest of microwave power transmission in space and for balloons plus substantial advances in the technology of packaging solid-state microwave rectifiers has stimulated interest in the flexible rectenna.

The flexible rectenna has a number of advantages for space in that it can be easily rolled up, stored, and then deployed when needed. The flexible rectenna can be adequately cooled by radiative processes alone, even when exposed to direct solar radiation and radiation from the Earth. Although microwave diodes are now available in sizes and shapes so that they could be incorporated into a flexible rectenna, it would appear that there is another stage of development of these devices in which the basic building block of the rectenna, namely the bridge circuit rectifier, which is composed of four diodes, could be made as a monolithic circuit on a single chip to be easily attached by welding or other means to the flexible rectenna.

Figure 17b illustrates some initial development work in the area of flexible printed circuits. The printed circuit in Figure 17b represents both the microwave dipoles as well as the dc power collector leads. It is made from a copper clad film material which consists of 1/2 mil thick copper clad to 2 mil thick Kapton. The flexibility of this configuration is aptly demonstrated in Figure 17b.

It may be desirable now to review the more detailed characteristics of the rectenna and of the microwave diodes, which are so essential to the concept and successful operation of the device.

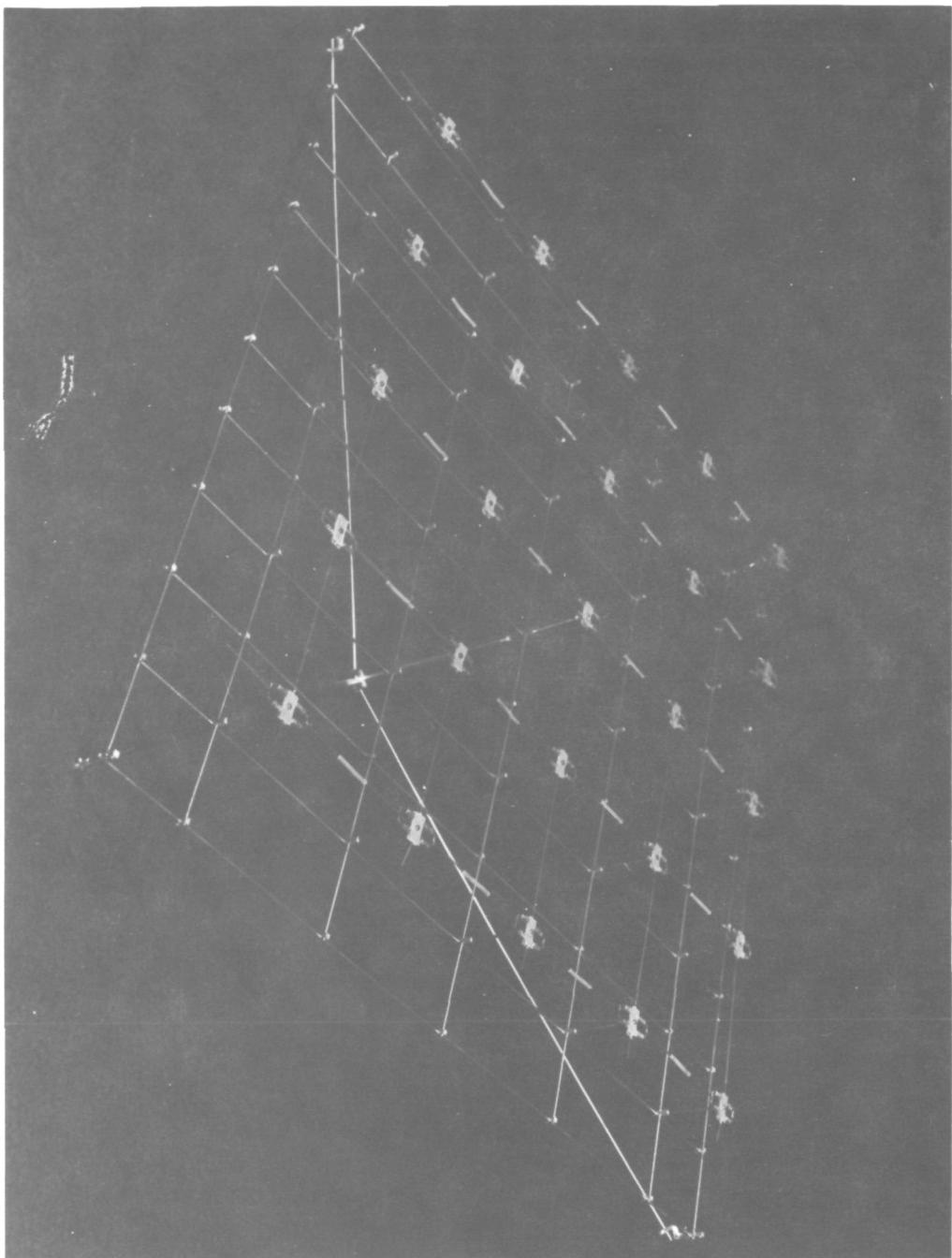


FIGURE 17a. PHOTOGRAPH OF RECENT RECTENNA MADE WITH SCHOTTKY BARRIER DIODES. (Structure weighs 20 grams and produces 20 watts.)

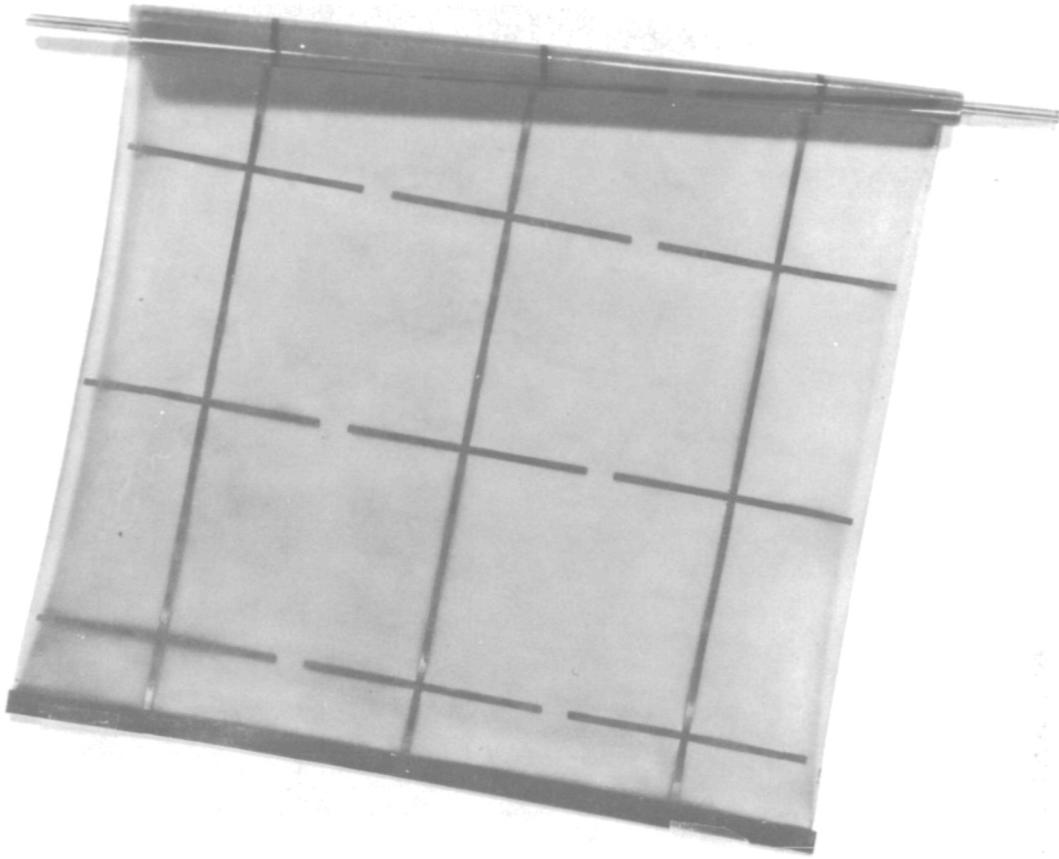


FIGURE 17b. PHOTOGRAPH OF PRINTED CIRCUIT APPROACH
TO A FLEXIBLE RECTENNA IN WHICH THE dc AND rf CONDUCTORS
ARE GENERATED BY PHOTOETCHING TECHNIQUE

It has been pointed out that the directivity of the device is not determined by the aperture size of the complete rectenna. Rather, it is controlled by the directivity properties of the smallest aperture into which the rectenna is divided. In the rectenna as illustrated in Figures 17a and 17b, the smallest aperture size corresponds to that of the half-wave dipole whose directivity is not very great. As a matter of fact, if the plane of the rectenna is inclined at 45 degrees rather than 90 degrees to the axis of the illuminating beam, its power output will only be reduced by 30 percent. The measured directional properties of a rectenna are typically those given in Figure 17c. As can be seen, the directional properties lie between those of a half-wave dipole and the simple cosine-law relationship corresponding to the reduction in illumination of an aperture when it is rotated.

ALL DIPOLES CONNECTED IN SERIES AND VERTICALLY POLARIZED.
 ALUMINUM PLATE REFLECTOR MOUNTED BEHIND DIPOLE ARRAY.
 LOAD RESISTANCE HELD CONSTANT AT 3500 OHMS.
 TEST FREQUENCY 2.44 GC. (DIPOLE = DIPOLE + DIODE)

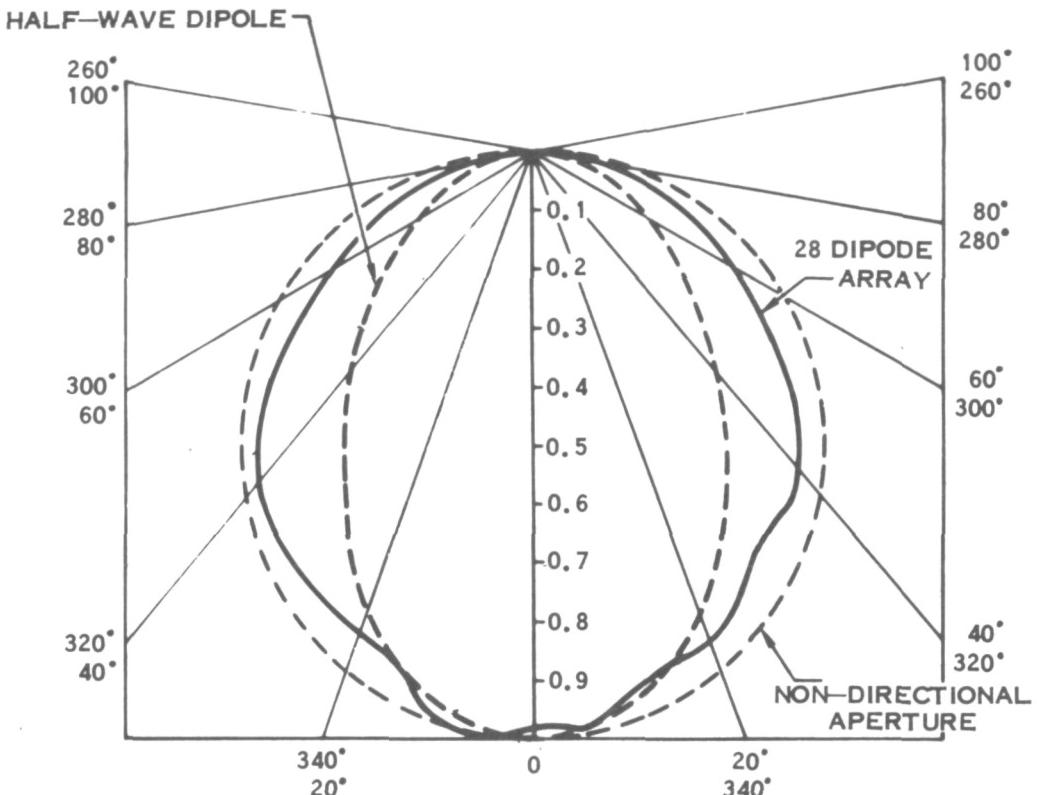


FIGURE 17c. MEASURED DIRECTIVITY OF A RECTENNA

Individual diodes that comprise the rectification portion of the rectenna can be highly efficient. Representative measurements made on Schottky barrier diodes of the type that are used in the rectenna configuration in Figure 17a are shown in Table III together with the output power levels which are involved. Also shown in Table III are the efficiencies of specially made diodes for operation in the higher frequency region of 8 MHz. It should be appreciated that even in the case of the diodes specially made for high frequency microwave application that an optimization of efficiency was not made. On theoretical grounds alone it would be expected that diode efficiencies in excess of 90 percent could be achieved.

TABLE III. PERFORMANCE DATA ON SCHOTTKY BARRIER DIODES

Type No.	Group No.	Test Freq.	dc Output/Diode		Efficiency %	Ref.
			Volts	Milliwatts		
A	SB-6	2.44 GHz	10.0	240.5	82.2	[35]
B	SB-6	2.44 GHz	10.0	300.0	75.0	[35]
C	#31-7	2.44 GHz	10.2	107.0	89.1	[35]
D	#31-7	2.44 GHz	10.2	137.2	85.7	[35]
E	HC-9-6	8 GHz	—	220.0	55.0	[36]

The overall efficiency of the rectenna then is determined by the product of the diode efficiency and the collection efficiency of the aperture. In general, the aperture should appear as an admittance plane in space which is matched to the incident microwave illumination. If this match is perfect then there should be no reflection and the collection efficiency should be 100 percent. Such efficiency can be approached by the use of a reflecting plane 1/4 wavelength behind the rectenna face and proper design of the rectenna face and choice of dc load. The rigid rectenna in Figure 17b is made in such a way that there is such a reflecting plane in back of the rectenna face, although it is not 100 percent efficient in its reflection and more grid wires need to be added in the reflecting plane. The flexible rectenna of Figure 17b would need to be deployed over an effective reflecting plane 1/4 wavelength removed from its surface. It should, therefore, be possible either for the flexible or rigid rectenna to achieve collection efficiencies close to 100 percent. With the best diodes, therefore, and 100 percent collection efficiency, there is an upper limit of about 90 percent overall efficiency. As a result, it is expected that 70 percent overall efficiency would be easily achievable. The major obstacle to receiving the very high efficiency would be to design the structure in such a way that the generation of harmonics will be minimized.

It was indicated that the rectenna could be adequately cooled by radiative processes. This can be achieved in part because of the high operating efficiency of the microwave diodes and in part because the heat is generated close to a radiative sink. The radiative sink consists of the rf and dc conductors which are attached to the rectifying diodes. In the limiting case, which in practice could be approached but not achieved, the diodes would be uniformly distributed over a continuous radiating area. If this area were a two-sided body with unity

emittance, and if its temperature were 150° C, a total of 3 360 watts (thermal) per square meter would be radiated (1820 watts/sq. meter from each side). If it were assumed that the only source of heat was the dissipation from the diodes and that the diodes operated at 80 percent efficiency, then a total of 14 650 watts of dc power (electrical) could be obtained from each square meter of surface area illuminated by microwave energy.

If the environments of the sun and the Earth are considered, these will provide additional heat inputs that must be considered. An extreme case would be full exposure and normality to the sun on one side of the radiating area and full exposure and normality to warm Earth on the other side. The sun's incident energy amounts to 13 350 watts/sq. meter, but as much as 95 percent* of this can be reflected with suitable surface finishes. (For example, see pages 8-37 of Handbook of Optical Properties for Thermal Control Surfaces LMSC-A847882, Vol. III. [13]) Under these conditions the absorbed solar power would be 62 watts. Reflection of the sun's energy by an Earth albedo of 0.32 and absorption of 5 percent of this by the rectenna would represent another 20 watts of power. Radiation from the Earth and absorption by the rectenna would be another factor and would represent about 20 watts. It is assumed that the Earth's radiation would be at the longer wavelengths and that 80 percent of it would be absorbed by the rectenna. Under certain conditions then, there would be a total of as much as 1100 watts/sq. meter of external power (thermal) absorbed by the rectenna, if it is assumed to be a continuous surface.

It must be recognized that the emittance of the rectenna surface will not be unity. However, the solar reflecting coating referred to has an emittance of 0.8 at a temperature of 150° C. The total radiated power (thermal) under these conditions will then be 2925 watts/sq. meter. Of this 2925 watts, 1100 watts will come from external sources, leaving 1825 watts as dissipation from the diodes. Hence, the total dc power output, assuming 80 percent efficiency, would be 7325 watts/sq. meter. But, if the top operating temperature were raised to 200° C, the permitted temperature of the newer Schottky barrier diodes, this figure would be raised by a factor 1.53 to 11 200 watts/sq. meter.

In many practical space applications it is anticipated that the power density requirements will be but a small fraction of this and that a practical arrangement would be diodes in the form of bridge-rectifiers placed 1/2 wavelength apart in an array. Under these circumstances it is found that the rf conductor inputs and the dc conductor outputs make excellent heat sinks. Temperature drops caused by heat conduction can be held to within a few tens of

*This value can be expected in the near future provided research effort continues at the present rate.

degrees and the conductors can be made of the proper width to radiate the required power. For example, if it is desired to operate at 215.5 watts/sq. meter, the conductor area need be only 3 percent of that of a continuous surface, assuming a 50° C temperature drop is provided for heat conduction and that the radiating surface is at a temperature of 150° C. Higher power outputs can be obtained with more radiating area.

Microwave Power Supply Converters at the Substation. The electric power output (of the rf converter) at the astronomical substation will be assumed to be dc. This will have to be converted to a suitable form for the most efficient operation of the substation instruments. For example, the dc power may be converted to an alternating current of 2.4 kHz, 400 Hz, or other, for distribution to the servo system, the telescope, and other instruments. Since 2.4 kHz supplies already are in use (Apollo and Mariner), there may be no special substation dc power-conversion problem. It is expected that these power supplies will be needed in most of the substation experiments and that the efficiencies will be from 85 percent to 90 percent.⁴

Beam-Riding System. The satellite substations will be unattended except for occasional servicing, changing of instruments, or recovery of film [1]; therefore, their position may be controlled automatically by beam sensors and a servo-controlled electric thruster system. The recent development of a microwave beam-sensing technique [28, 40] may be applicable to the control of the substation receiving antenna.

Raytheon Company under contract [No. AF 30(602) 4310] to Rome Air Development Center has designed a control system that automatically keeps an electrically powered helicopter positioned on a microwave beam [15, 28, 40]. The microwave beam itself serves as a position reference for motion in five degrees of freedom: pitch, roll, yaw, and X and Y translation (Fig. 18). In this technique, any error information from the sensors is processed to apply the proper amount and direction of cyclic pitch on the helicopter rotor to maintain the helicopter toward the center of the microwave beam.

There are two types of sensors: amplitude- and phase-sensitive. The amplitude type is used as reference for yaw and for longitudinal (X) and lateral (Y) translational motion. The phase sensors are used as reference for roll and pitch. Properties of the microwave beam that make it suitable for use as a position reference are the decrease in beam intensity off the beam axis in the X and Y directions, a surface of equal phase normal to the beam axis, and polarization of the beam.

4. Discussion with Mr. H. J. Fichtner, R-ASTR, MSFC

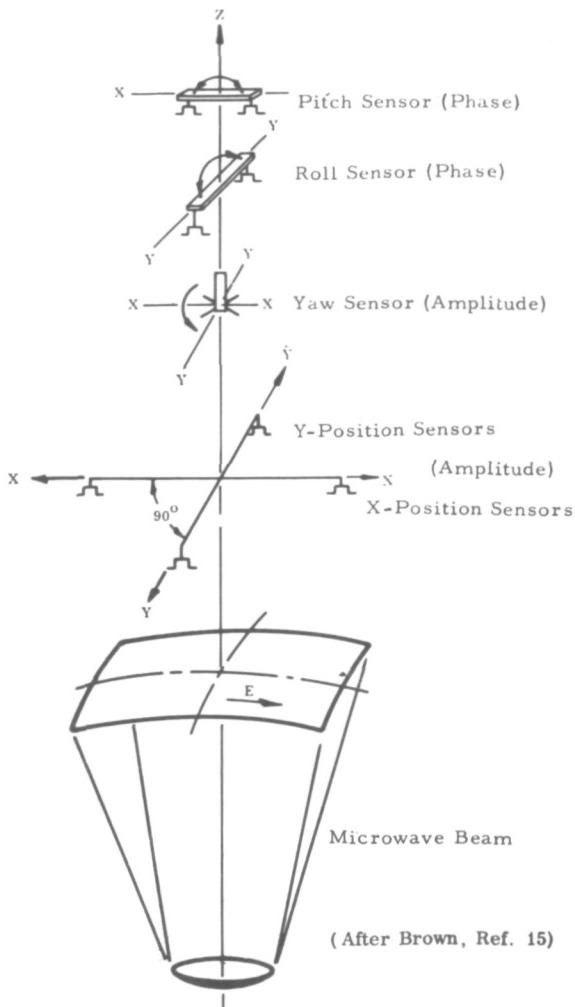


FIGURE 18. MICROWAVE BEAM AS
REFERENCE FOR FIVE POSITION
CONTROLS

put together.

When these individual efficiencies are examined in terms of their significance to the OAS, there are three classes of efficiencies of interest: (1) those that have been experimentally obtained in the past, (2) those which can be obtained using present state-of-the-art components, and (3) those which might be reasonably expected in the future if an attempt is made to maximize efficiencies on the basis of today's knowledge on how to approach the problem of doing so.

The entire control system consisting of microwave beam, microwave sensors, autopilot, and helicopter has been extensively tested. Figure 18a shows the helicopter stably positioned in free flight on the beam. The only attachments are the cable which supplies the power to the electric motor and monitoring cables.

OVERALL MICROWAVE POWER TRANSMISSION EFFICIENCIES

There are three major elements of efficiency in microwave power transmission: (1) microwave power generation efficiency starting from the dc power input, (2) microwave transmission efficiency from the output of the generator to the receiving aperture, and (3) collection and rectification efficiency at the receiving point. When these three efficiencies are multiplied together the overall efficiency as measured in terms of the ratio of the dc power out of the system to the dc power input to the system is established. Presumably if these efficiencies have been obtained independent of each other, the overall efficiency should be their product when they are

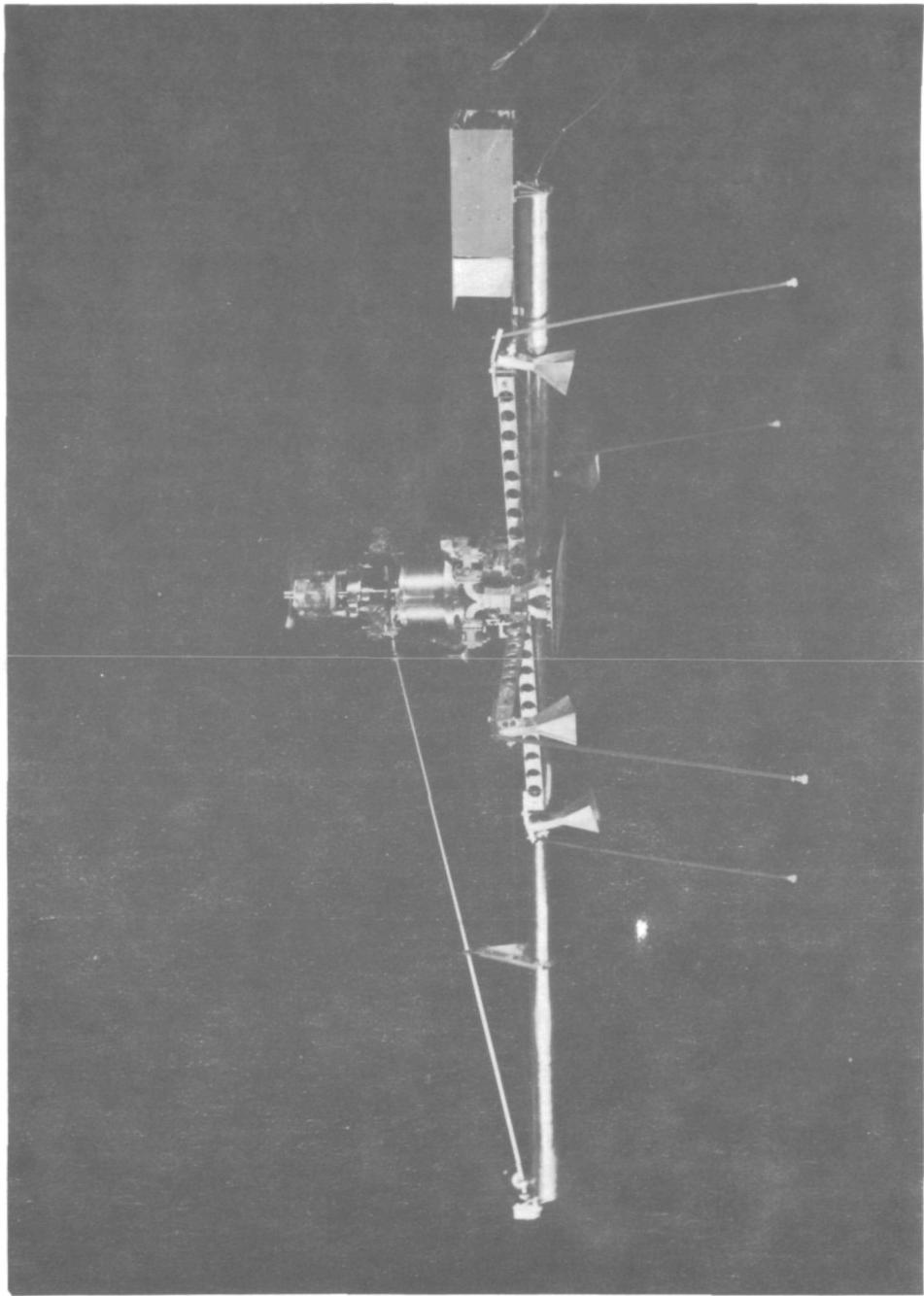


FIGURE 18a. PHOTOGRAPH OF HELICOPTER BEING AUTOMATICALLY POSITIONED IN FREE FLIGHT BY MEANS OF POSITION INFORMATION AVAILABLE FROM A MICROWAVE BEAM
(Cables shown in photograph are monitoring cables and power cable to electric motor.)

These various efficiencies are given in Table IV. While the overall efficiency using experimental data indicates 26.2 percent it should be possible to obtain 47.5 percent overall efficiency on the basis of today's technology. In the longer range picture an efficiency of up to 69 percent may be possible.

SUMMARY OF MICROWAVE POWER TRANSFER

Transmission of power over a microwave beam has been demonstrated experimentally. Components are available for the transfer of several kilowatts over a distance of several kilometers. It should be feasible to adapt these components for use in the orbiting astronomical project.

Research and development in microwave generation have been going on for 25 years, and have resulted in equipment which can generate the microwave power required for the proposed astronomical station. An obvious implication of the calculations on antenna size and operating wavelength (Fig. 16) is that work on superpower generators should be directed toward efficient operation at shorter wavelengths (smaller than 3 cm). Research and development in microwave receiving systems constitute a relatively new field of endeavor.

While much promise is offered by the diode rectifiers being investigated, other components should be reexamined since continuing improvements in their efficiency may now make them as useful as the diodes. Other approaches also should be reevaluated. For example, using a local oscillator, heterodyning incoming microwave power down to a frequency of 2.4 kHz for distribution would eliminate a dc-to-ac converter and improve overall efficiency.

TRANSFER OF POWER BY LASERS

The development of lasers for high output powers is a relatively new field of investigation, with most of the effort being in the research phase. For this reason the possibilities of their use in wireless power transfer cannot be reported to the extent done for microwaves.

TABLE IV. MICROWAVE POWER TRANSMISSION EFFICIENCIES

	Efficiency Presently Demonstrated	Efficiency Expected With Present Technology	Efficiency Expected With Additional Development
Microwave Power Generation	76.7% ^a	85% ^d	90% ^g
Transmission Efficiency from Output of Generator To Collector Aperture	66% ^b	80% ^e	90% ^h
Collection and Recti- fication Efficiency (Rectenna)	52% ^c	70% ^f	85% ⁱ
Overall Efficiency dc Output/dc Input	26.2%	47.5%	69%

a. Measured efficiencies on QK1224 Amplitron while producing 300 kilowatts of CW power [41]. References 42 and 43 report a measured Amplitron efficiency of 79 percent at 1.4 megawatts output on Amplitron type 1493, number 2.

b. Experiment at Spencer Laboratory, Raytheon Company, 1963 [44].

c. Data taken by Prof. R. H. George of Purdue University [45].

d. Data taken at Raytheon on special Amplitron designed for high efficiency. See page 50 of Reference 39 for description of tube and operating data. 89 percent efficiency was the actual measurement but validity of data is ± 4 percent, so 85 percent as stated above is a conservative value.

e. Assumes that gaussian illumination efficiency of transmitter aperture can be raised to 93 percent and that receiving aperture is capturing 86 percent of beam. ($r = \omega$)

f. Assumes use of new Schottky barrier diodes operating at 80 percent efficiency and antennas with 87.5 percent capture efficiency. These are reasonable values based on published measurements of diode efficiency of as high as 89 percent by George, and the concept of the rectenna as a matched admittance plane [46].

g. Use of very high magnetic field and vane shaping in Amplitrons to optimize efficiency [39, pages 41-60].

h. Further increase in transmitter aperture illumination efficiency and use of larger receiving aperture.

i. Additional development work on semiconductor diodes and reduction of harmonic losses.

Laser Power Generation

Laser power output and efficiency have been improved rapidly since the first demonstration of the continuous-wave gas laser in 1961. At that time Javan's He-Ne laser had a power output of 0.1 W/m of laser tube, and an efficiency of about 0.1 percent [20]. In recent experiments with gas lasers (CO₂-N₂-He medium), continuous power of 1.2 kW was obtained in a 20 m tube, at 17 percent efficiency, and a linear power density of 80 W/m was obtained in a 3 m tube [21]. These values were obtained with gases flowing through the tube, however, with a fixed volume of gas in a sealed-off tube, the maximum linear power density was 28 W/m, at 7 percent efficiency.

The highest power output known at present is 9 kW, obtained at Raytheon Company Research Laboratory (under contract to Physical Sciences Laboratory, Redstone Arsenal.)⁵ The laser in this investigation is made of nine modules, each 15.2 m (50 ft) long, arranged side by side to shorten the laser housing. It is expected that under improved operating conditions (increased pump capacity at each module and cooling of the module walls) and the addition of six more modules, the output will be increased to 10 kW.

The high-power CO₂ lasers are large and bulky, and require much supplementary equipment. Their quasi-theoretical upper limit of efficiency as energy generators has been estimated to be 40 percent⁶ [21], in comparison with 70 percent - 80 percent for Amplitrons. Despite the present shortcomings, however, work on high output powers for lasers is heavily funded in military weapons studies. If progress continues at the same rate as in the past 5 years, engineering models of laser power generators should be available in about 5 more years [22].

Laser Power Transmission

In electromagnetic energy transmission, reflectors are used for microwave frequencies; and refraction techniques are usually used for the visible frequencies. The frequency of the CO₂ laser output (10.6 μ , in the middle infrared) falls between the visible and the microwave frequencies. Both refraction and reflection techniques are being used in laser studies, but refraction systems, being much smaller and lighter, would be preferable.

5. Discussion with Dr. H. Statz, Raytheon Company, Waltham, Mass.

6. Discussion with Dr. J. A. Merritt, U. S. Army Missile Command, Redstone Arsenal.

The heating effect of the infrared wavelengths, however, presents special problems in the use of refractors (i.e., lenses). Rigden and Mueller [23] have pointed out that there are relatively few solids or liquids that do not have a high absorption for 10μ radiation. Consequently, most materials become incandescent and tend to burn up when exposed to the high-power beam of CO₂ lasers.

Several salts have been used as laser beam refractors. Irtran 4 has been the best of the zinc selenide types, but its efficiency of 94 percent is too low to allow its use for high-power beams. Refractor materials with an efficiency closer to 100 percent (for minimum absorption of destructive heat) are needed to withstand the very high temperature of beams in the kilowatt power level. The only high-efficiency materials which have been used in experimental work are NaCl and KCl (99% efficiency), but their eventual deterioration makes them unsuitable for long-term practical operation [21]. (NaCl output mirrors, for example, have several disadvantages: NaCl is hygroscopic and soft, the surface cannot be cleaned, dust particles tend to settle on the surface and burn in, the internal surface becomes altered so that the optical quality deteriorates, it creeps under thermomechanical strain and so produces surface curvature, and it cracks after several hours of exposure to the laser beam.)

Ultra-pure germanium is being investigated as a lens material for high-power levels [21], but it, too, has an inherent disadvantage of poor operation because of heat absorption. A doped germanium lens (Ge-Sb-Se) with an efficiency of 98% also is being tested, but results have not been published.⁷

The technology of high-power transmission by lasers obviously is in too early a stage for conjecture on its practicality. Nevertheless, laser power transmission is being considered as a possibility in the orbiting astronomical concept because it has potential advantages over microwave transmission. As it will be shown, the laser beam requires a transmitting aperture that is very small compared with the microwave antenna, and the same advantage applies at the receiving end of the power link. In addition, a much narrower beam can be projected, even for great distances. This is an ideal condition for an electromagnetic link since the narrowness of the beam minimizes the engineering problems of compromising between antenna sizes and efficiency of power transfer.

7. Discussion with Mr. G. J. Hutcheson, U. S. Army Missile Command, Redstone Arsenal.

The relationship between antenna diameter, wavelength, and separation distance, as used for microwaves, applies as well to laser power transfer. Thus, for a CO₂ laser wavelength of 10.6 μ and the same distances between central station and substation (5, 2, and 1 km), the aperture diameters are very much smaller than for microwave transmission. This is illustrated in Figure 19, for the same 84% power capture as in the calculations of the microwave antenna diameters. The size of the antenna apertures increases with increasing length of the beam path, as it was shown in Figure 16 for microwaves. However, the beam path length is not a limiting factor for antenna size to the extent it is for microwaves.

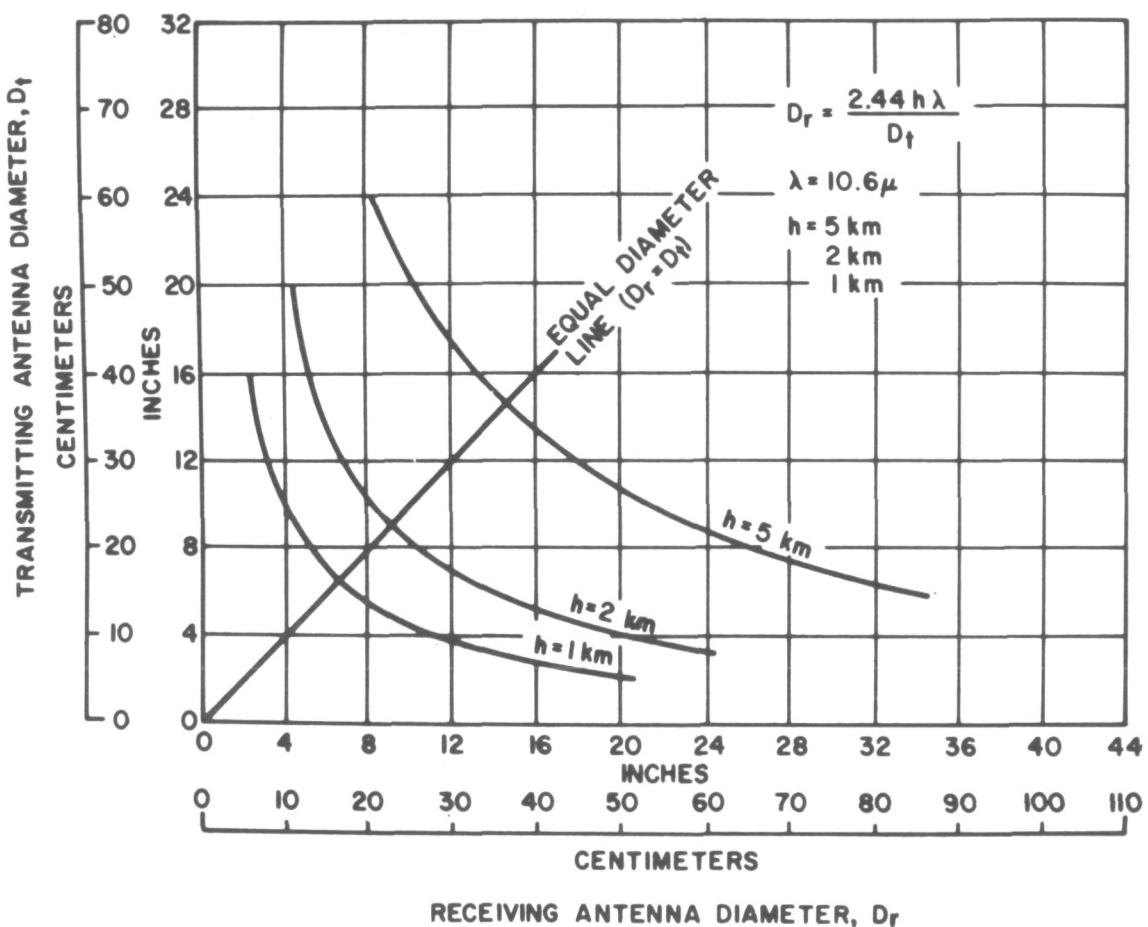


FIGURE 19. CALCULATED ANTENNA DIAMETERS FOR THREE SEPARATION DISTANCES AND A LASER WAVELENGTH OF 10.6 μ

Laser Power Reception and Conversion

Antennas. Just as for the transmitting aperture, the receiving antenna can be smaller than its microwave counterpart (at least an order of magnitude). Therefore, where receiving-antenna size may be strictly limited for a small substation, the antenna size may not be a serious problem for a laser system. The substation may even be able to carry a receiving antenna sufficiently large for better capture than the calculated 84%.

Conversion of Laser Power to Electric Power. There are no detectors presently available for the conversion of high levels of laser power. The most promising possibility for the conversion of laser energy to dc power may be photovoltaic detectors.

A new method of doping p-n junctions has been reported by Vérié and Ayas [24]. The junctions are made of $\text{Cd}_{x} \text{Hg}_{1-x} \text{Te}$ alloys, which are small bandgap semiconductors for certain values of x ($0.15 < x < 0.30$). The special p-n junctions are produced through the diffusion of interstitial atoms of Hg in p-type $\text{Cd}_{x} \text{Hg}_{1-x} \text{Te}$ single crystals. The result is a crystal with properties of electrical rectification, photovoltage, and electroluminescence. Photovoltaic detectors have been made with these crystals: they were operated at 77°K and showed responses from 3μ to 17.5μ . According to the investigators, the results indicate that $\text{Cd}_{x} \text{Hg}_{1-x} \text{Te}$ p-n junctions should be usable for rectification of CO_2 laser radiation.

This development also indicates the probability of very good efficiencies. The bandgap of these semiconductors is very small and can be tailored to function at a wavelength of 10.6μ . The theoretical efficiency has been calculated to be close to 100%, and practical diodes with an efficiency of 70% may be possible.⁸ Since the output power of a single detector diode would be very small, many diodes could be arranged in a suitable array to provide the proposed 2kW requirement for an astronomical substation.

8. Discussion with Dr. H. Statz, Raytheon Co.

COMPARISON OF THE TWO METHODS OF WIRELESS POWER TRANSFER

Power Generation

Research in laser-power generation has progressed rapidly in the few years of its history, but it is too recent to have provided power levels competitive with microwave power generation. The efficiencies and power outputs for both methods are summarized graphically in Figures 20 and 21, respectively.

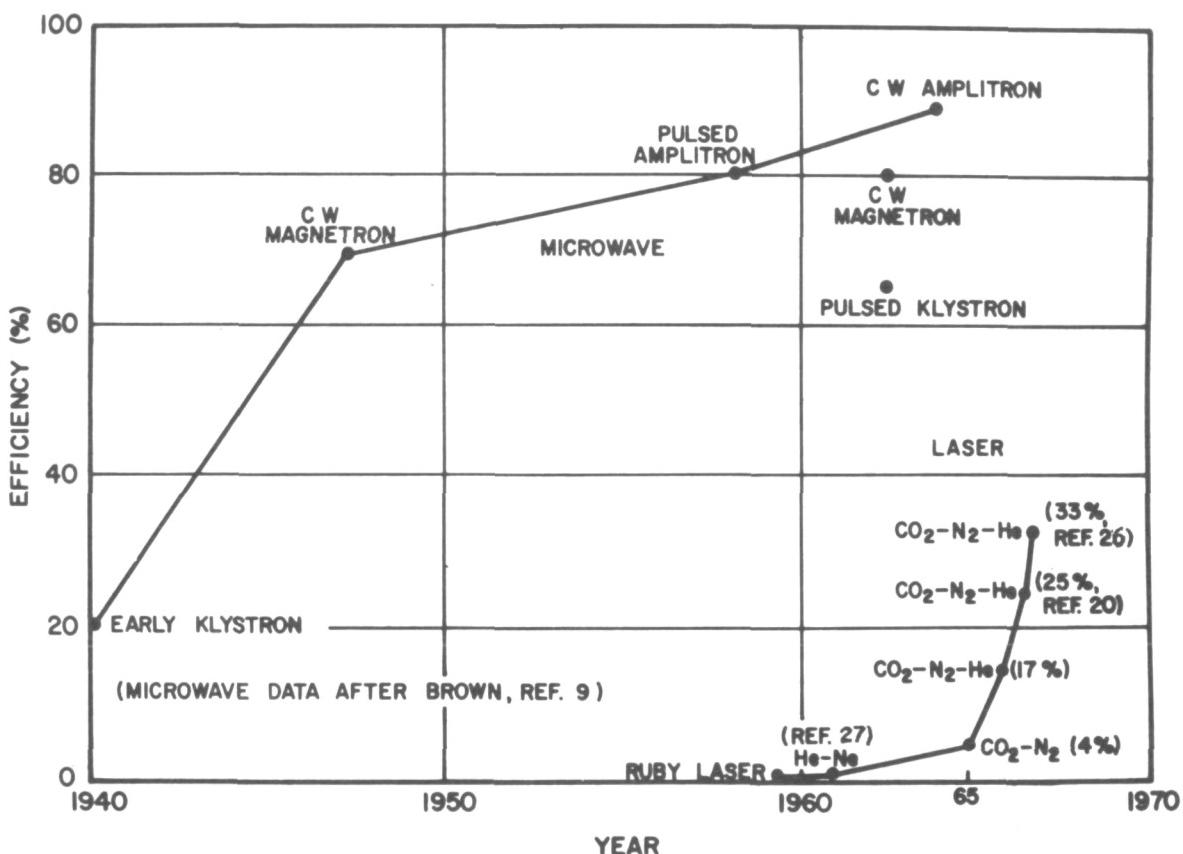


FIGURE 20. DEVELOPMENT OF EFFICIENCIES OF LASERS AND SINGLE MICROWAVE GENERATORS

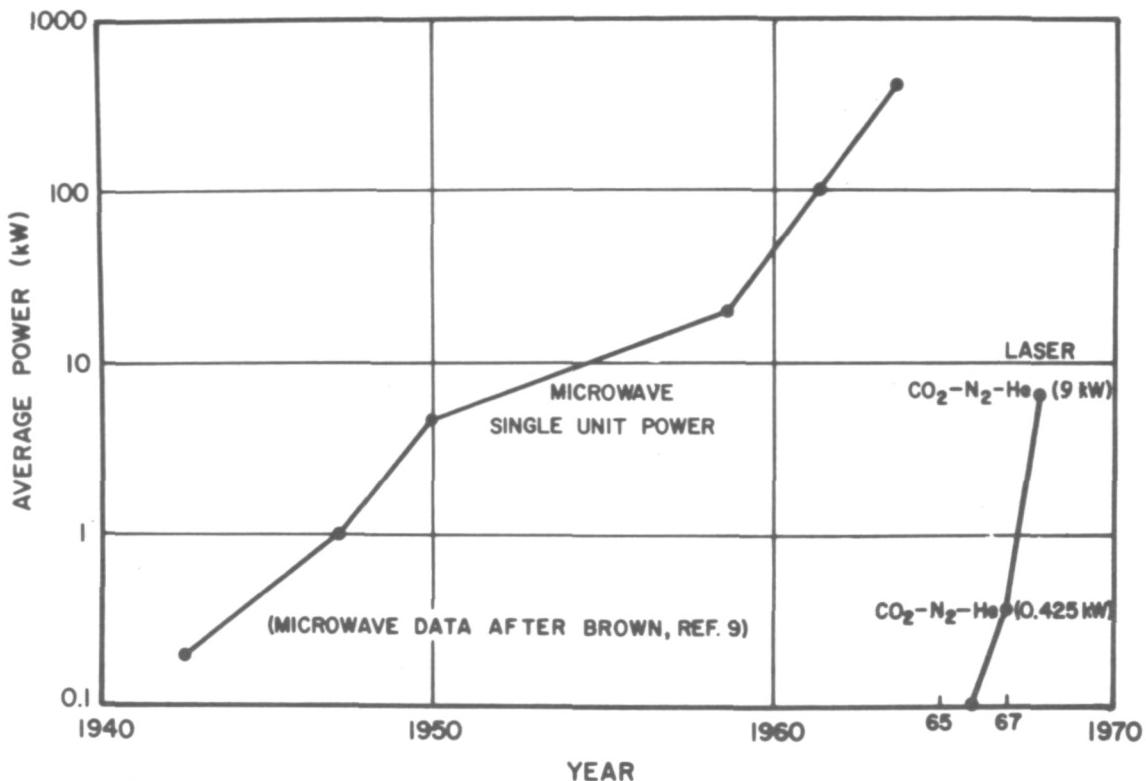


FIGURE 21. DEVELOPMENT OF POWER OUTPUT OF LASERS
AND SINGLE MICROWAVE GENERATORS

Microwave power output (over 400 kW at 70% - 80% efficiency for Amplitrons) is more than adequate for the 10 kW - 20 kW estimated requirement of an orbiting astronomical station; moreover, it is generated by long-lived, relatively small, proven industrial components. The maximum output power of lasers, 9 kW, is insufficient for the estimated requirement, and is obtained with bulky laboratory equipment. However, since investigations on high-power laser output are being actively supported, there is good reason to believe that the needed power output will be available before 1975.

An assessment of the feasibility, in the next few years, of power generation for an electromagnetic link points to microwaves as the likely source of energy. For longer-term feasibility (within 10 years) lasers are expected to supply the required energy.

Power Transmission

Transmission of power over a microwave beam has been demonstrated experimentally, and investigations of long distance transmission for control as well as power transfer are in progress.

The newer field of laser power generation has not reached this state of development. Even suitable materials and components (for example, mirror coatings and lenses) are still in the research or developmental stage.

In studies on theoretical power density distributions, particularly those following a Fraunhofer diffraction pattern, calculations indicate that a laser system would require very much smaller transmitter (and receiver) apertures than microwave systems. This potential advantage of a laser system may justify continued work toward the development of a practical laser high-power transmission system.

Power Reception and Conversion

Reception and conversion of high levels of electromagnetic energy have lagged behind power generation. This state may be attributed to the fact that the need for efficient conversion had not been emphasized until high levels of microwave energy were made possible through the development of "super-power" microwave generators.

While reception and conversion of high-energy radiation are relatively new fields of study, such study has had an earlier start in microwave application. The rectenna used in Raytheon's helicopter experiment already has demonstrated the practicality of semiconductors in microwave conversion to electricity. Still in the developmental stage, the close-spaced thermionic diode rectifier has produced up to 900 W of dc power. Electric conversion of laser energy is only in the research stage. Semiconductor diodes (doped p-n junctions of $\text{Cd}_x\text{-Hg}_{1-x}\text{Te}$ alloys) have been used experimentally as photovoltaic detectors. This is a promising development since their bandgap is very small and can be adapted for CO_2 -laser operating wavelength. Moreover, the diode efficiency may be very high.

CONCLUSIONS

This study points out that wireless power transmission is not only feasible but has been demonstrated to be workable. The design and development of microwave-system components are sufficiently advanced to justify the expectation that a practical microwave high-power transmission system for use in space could be available within a few years.

One of the estimated disadvantages of a microwave power system is the antenna size, which would be large for maximum power-transfer efficiency. A laser system would eliminate this disadvantage. Moreover, its very slight beam divergence would make the laser system especially suitable for power transmission in space beyond several kilometers.

Since the laser is well behind microwaves in research, development, and available devices for system design, laser research and development programs should be strengthened now, so that a practical system will be ready in 5 to 10 years.

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APPROVAL

THE FEASIBILITY OF WIRELESS POWER TRANSMISSION FOR AN ORBITING ASTRONOMICAL STATION (REVISED)

By

William J. Robinson, Jr.

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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